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TECHNICAL

TN NO: N-1703

TITLE: EVALUATION OF NONDESTRUCTIVE UNDERWATER TIMBER INSPECTION TECHNIQUES

20030109221

AD-A147 537

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DATE: August 1984

SPONSOR: Naval Facilities Engineering Command

PROGRAM NO: YF60.534.091.01.202B

NOTE

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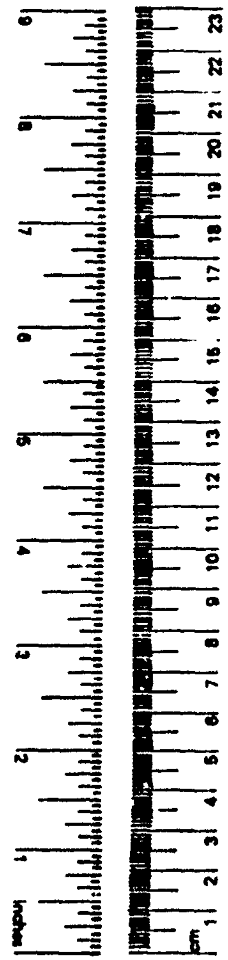
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

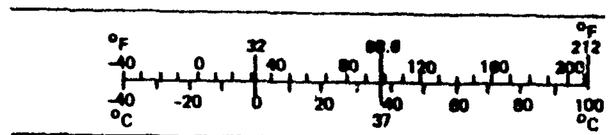
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2,000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1,000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: TN-1703
2. GOVT ACCESSION NO.: DN044010
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): EVALUATION OF NONDESTRUCTIVE UNDERWATER TIMBER INSPECTION TECHNIQUES
5. TYPE OF REPORT & PERIOD COVERED: Not final; Jun 1981 – Aug 1983
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): C. A. Keeney and S. E. Pollio
8. CONTRACT OR GRANT NUMBER(s):
9. PERFORMING ORGANIZATION NAME AND ADDRESS: NAVAL CIVIL ENGINEERING LABORATORY, Port Hueneme, California 93043
10. PROGRAM ELEMENT PROJECT, TASK AREA & WORK UNIT NUMBERS: YF60.534.091.01.202B
11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Facilities Engineering Command, Alexandria, Virginia 22332
12. REPORT DATE: August 1984
13. NUMBER OF PAGES: 58
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS (of this report): Unclassified
15a. DECLASSIFICATION DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report): Approved for public release; distribution unlimited.
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number): Underwater inspection, nondestructive testing, waterfront facilities, ultrasonic testing, impact testing, computerized axial tomography, timber inspection
20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

This report presents the assessment of potential techniques for underwater nondestructive testing of timber piles. Three techniques are discussed: X-ray tomography, indirect ultrasonic testing, and impact testing. A computerized axial tomography (CAT) system has never been used underwater to date. However, studies concluded that the underwater application of tomography is technically feasible. A brief introduction to the proposed prototype underwater CAT system is presented. In addition, results of laboratory

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and field tests to evaluate the capability of an indirect ultrasonic system and impact system to accurately measure the percent cross-sectional wood loss are presented in detail.

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Naval Civil Engineering Laboratory
EVALUATION OF NONDESTRUCTIVE UNDERWATER TIMBER INSPECTION TECHNIQUES, by C. A. Keeney and S. E. Pollio
TN-1703 58 pp illus August 1984 Unclassified

1. Underwater inspection 2. Nondestructive testing I. YF60.534.091.01.202B

This report presents the assessment of potential techniques for underwater nondestructive testing of timber piles. Three techniques are discussed: X-ray tomography, indirect ultrasonic testing, and impact testing. A computerized axial tomography (CAT) system has never been used underwater to date. However, studies concluded that the underwater application of tomography is technically feasible. A brief introduction to the proposed prototype underwater CAT system is presented. In addition, results of laboratory and field tests to evaluate the capability of an indirect ultrasonic system and impact system to accurately measure the percent cross-sectional wood loss are presented in detail. Originator-supplied Keywords include: ->(Form 1473)

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE(When Data Entered)

CONTENTS

INTRODUCTION

Accurate assessment of the condition of Naval shore facilities is a vital aspect of Fleet readiness. More than two-thirds of the Navy's waterfront structures were built before 1950 and are rapidly deteriorating. Thirty-five percent of Navy piers are wooden superstructures on wooden piles (Ref 1). An economical maintenance management program for these structures requires development of reliable and accurate underwater timber inspection techniques.

In 1979, the Naval Civil Engineering Laboratory (NCEL), under the sponsorship of the Naval Facilities Engineering Command (NAVFAC), initiated a project to improve the Navy's ability to inspect and assess the soundness of the underwater portion of wooden waterfront facilities. The state-of-the-art of underwater nondestructive testing (NDT) and the application of existing or potential NDT techniques were to be evaluated. This report presents the results of laboratory and field evaluation of several potential techniques, particularly acoustic NDT techniques.

BACKGROUND

Natural materials, such as wood, often vary inherently to a large degree, and prediction of their properties is considerably more difficult than with man-made materials. Distinguishing the natural property variations from any internal damage of the wood under water has been a major effort at NCEL, and several approaches have been investigated. The types of timber damage, the measurement accuracy requirements for timber piles, and the initial concepts for inspecting wooden waterfront structures are discussed in this report.

DAMAGE

Structural damage of timber waterfront structures generally falls into one of two categories: mechanical or biological (Ref 1). Mechanical damage usually results from accidental overloads or abrasion. Accidental overloads can occur during construction from excessive pile driving forces or after construction from large impact loads, such as docking ships. Abrasion typically occurs in the intertidal zone and depends upon the amount and type of material or debris in the water.

Biological damage to wooden waterfront structures results from the activities of living organisms such as fungi, insects (e.g., termites, ants), and marine borers. Fungi, the cause of wood rot, are low forms of plant life that depend on organic materials for food. Rot damage usually occurs above water in the splash zone and near the pile cap. Insect damage also occurs above water in the atmospheric and splash zones.

The most severe type of damage to timber waterfront structures is caused by marine boring organisms because this damage often cannot be detected visually until extensive damage has been done. In the United States alone, marine borers and fungi annually cause an estimated $500 million in damage to wooden waterfront structures (Ref 2).

Marine borers are of two types: crustaceans and mollusks (Figure 1). Of the crustaceans, Limnoria or Woodgribbles are of primary importance. The shrimp-related Limnoria attack and damage wood at the piling surface. These tiny animals average 1/8 to 1/4 inch in length and burrow shallow tunnels which are then eroded away by wave action, exposing new wood to attack. Limnoria eventually narrow the pile diameter usually at the waterline (or the mudline), resulting in an hourglass shape.

The molluskan type of marine borers are teredines and pholads. Teredines are commonly referred to as Shipworms and include Teredo and Bankia. Shipworms settle into the wood substrate when they are very young and barely visible. Their clamlike shells begin digging into the wood leaving a pinhole entrance. They burrow inwards and eventually turn to tunnel along the soft wood grain. Teredines can cause severe loss of structural integrity and leave essentially no externally visible signs. The average size of adult Teredo is 1/2 to 1 inch in diameter and 1 to 2 feet long. Unlike Limnoria damage, Teredo or Bankia damage usually cannot be detected by visual inspection.

Pholads or Martesia are approximately 2 inches in length and 1 inch in diameter as adults. Typically, Martesia burrow less than 2-1/2 inches into the piling but leave an entry hole large enough to detect visually.

MEASUREMENT ACCURACY REQUIREMENTS

The extent and severity of boring damage, coupled with the large number of wooden waterfront structures, necessitate development of quick and effective timber inspection techniques. These techniques must be capable of evaluating remaining structural strength or remaining cross-sectional area. If the timber pile sustains internal damage, then a parameter other than diameter must be used as an indication of structural condition.

Inspection data criteria and accuracy requirements were established, based upon structural analyses (see Ref 1). Table 1 lists the accuracy requirements as a function of (1) type of deterioration (internal or external); (2) load capacity of the column; and (3) length of the damaged section (with respect to the total length of the pile) for various degrees of damage. Thus, Table 1 defines the physical and material parameters to be measured and the level of accuracy to which they must be measured. The accuracy is given in terms of coefficient of variation (%), which, in statistical terms, is the standard deviation divided by the mean.

With more than one-half the original cross-section remaining, the requirements for accurate measurement are as follows:

1. For extensive external damage to the piles, 14% (most stringent requirement)

2. For internal damage from Teredo and Bankia, 20%

Therefore, the test and evaluation of potential underwater timber inspection techniques were based upon the 14 and 20% accuracy requirements.

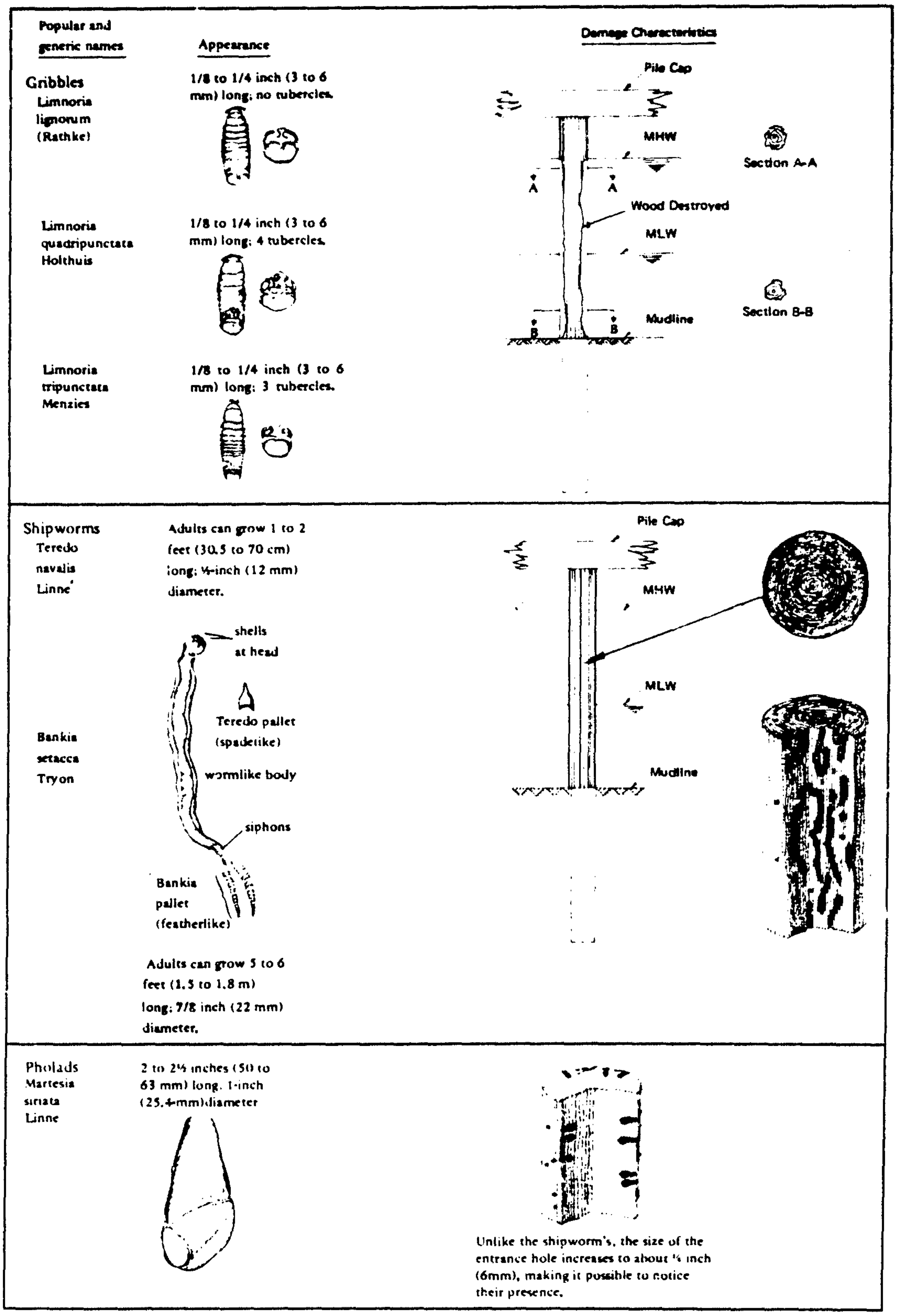


Figure 1. Characteristics of marine borers.

Table 1. Accuracy Requirements for Timber Piles

[Nomenclature at end of table.]

Structural Evaluation Criteria	Type and Extent of Deterioration	Field Data Required		Accuracy Requirement (±%)
		Parameter	Range	
A. Material Strength	Internal Damage			
$f_a = P/A$	1. Magnitude - cross-sectional area:			
or	$A_R/A_0 > 0.5$	A_R	50-150 in.^{2}	20
	$A_R/A_0 < 0.5$	A_R	0- 75 in.^{2}	25
B. Instability				
	2. Length/location	L_d, H_d	>1-2 ft	20
Short Column:				
$f_c = \frac{1}{3} - \left(\frac{\ell/r}{\ell/r'}\right)^4$	External Damage			
	1. Confined damage region:			
applied where $f_c \leqq (2/3)F_c$	$L_d/L \leq 0.2$	L_d	1-8 ft	20
	$A_R/A_0 > 0.5$	A_R	50-150 in.^{2}	20
Long Column:		d_R	8-14 in.	10
$f_c = \frac{\pi^2 E_L}{(\ell/r)^2}$	$A_R/A_0 < 0.5$	A_R	0-75 in.^{2}	25
	Location	H_d	>1-2 ft	20
	2. Extended damage region:			
	$L_d/L > 0.2$	L_d	>8-10 ft	2
	$A_R/A_0 > 0.5$	A_R	50-150 in.^{2}	14
		d_R	8-14 in.	7
	$A_R/A_0 < 0.5$	A_R	0-75 in.^{2}	25
	Location	H_d	>1-2 ft	20

A = cross-sectional area

A_0 = original cross-sectional area

A_R = remaining cross-sectional area

d_R = diameter of remaining cross-sectional area

f_a = axial stress

f_c = critical stress for a column

H_d = location of damaged section along pile length, distance from pile cap to seabed or to midpoint of damaged section

L = total length of structural element

L_d = length of damaged section

ℓ = unsupported length

P = axial load

F_c = critical buckling stress

r = radius of gyration

E_L = modulus of elasticity

The accuracy needed could be established based on the criteria for maintenance. The degree of damage determines the method of repair. Piling is wrapped when damage is between 5 and 15% of the cross-sectional area. When damage is between 15 and 50%, the piling is repaired with grout or concrete. When damage exceeds 50%, the piling or the damaged area is replaced with wood or concrete (Ref 3). For both economic and safety purposes, the accuracy required should be between 10 and 15%. After 15% cross-sectional area loss, the strength of the pile is affected and the cost for repair increases.

Current methods of inspecting waterfront structures do not meet the accuracy required to prevent unexpected or catastrophic failures, particularly in critical waterfront facilities that directly impact Fleet operational readiness. Current methods of inspection include visual surveys, incremental coring, resistance probing, and hammer sounding. In addition, ultrasonic inspection of wood piles is currently being used by Agi and Associates, a consulting firm located in Vancouver, British Columbia, which has often inspected Navy facilities.

Visual inspection, the most common method of inspecting underwater structures, is an essential part of any structural survey and can provide information on defects and external condition. However, numerous defects are not visually detectable, particularly in timber waterfront structures. Pilings that appear to be sound may suffer over a 50% loss in cross-sectional area from marine borer infestation. In core sampling one or more small diameter cores are removed for examination to determine the internal condition of the piling. Core samples indicate the pile condition in the exact location of the core. The major disadvantage of incremental core inspection is the small probability of intersecting a mollusk tunnel unless the infestation has reached advanced stages. Resistance probing and hammer sounding give only gross indication of internal condition and are typically only successful in identifying extensive deterioration.

The ultrasonic equipment used by Agi and Associates was developed by B.C. Research of Vancouver, British Columbia. B.C. Research studies revealed that the remaining cross-sectional area could be correlated with the ultrasonic measurement only to within 25%. This is due to the inherent variations in wood strength and the effects that differing eccentricities of the damage in the cross-sectional area have on the buckling and bending moments for the pile (Ref 4). The detailed capabilities of the ultrasonic inspection technique used by Agi and Associates are discussed in this report in the section on Commercial Ultrasonic Capabilities Demonstration.

POTENTIAL TECHNIQUES

Passive Sonic Testing

During research to determine growth rates of Bankia and Teredo, Professor E.C. Haderlie of the Naval Postgraduate School, Monterey, Calif., found he could detect the presence and location of borers in timber laboratory test panels. The borers were detected by listening

with a sensitive transducer for the rasping sound produced by the organisms as they bored into the wood. As a follow-on to this work, NCEL sponsored a project to determine the feasibility of using this technique to detect the presence of marine borers in timber piling. In the first phase of the work, isolated specimens of Bankia and Limnoria were collected and their characteristic sound spectra recorded in the laboratory. It was hoped that the sounds made while boring would be unique in spectral content and could, therefore, be distinguished from ambient background noise present in all waterfront environments.

Test results revealed that the sonograms of isolated mollusks and gribbles were almost identical to the ambient noise recorded in Monterey Harbor. In his final report (Ref 5), Professor Haderlie concluded that "...the natural sound of barnacles and other foulers on a piling are so diverse and complicated that they mask any borer sounds coming from within the piling and we have been unable to filter out the extraneous sounds which might make it possible to detect borers in a wooden harbor structure."

Low Frequency Ultrasonics

In an early state-of-the-art survey (Ref 6) low frequency ultrasonic NDT was identified as having the greatest potential for improving the Navy's ability to accurately evaluate the integrity of wooden waterfront structures. This NDT method was selected for further evaluation because it is known to penetrate through wood, is not hazardous to work with, and can be readily used in an underwater environment.

Low frequency ultrasonic inspection is based upon the influence of the test specimen on the propagation of a known sound wave. In flaw detection, the transit time of an ultrasonic pulse traveling through a test specimen with a fixed path length is measured. Dividing the path length or the separation distance between two transducers by the transit time determines the acoustic velocity. Solid homogeneous materials have a constant acoustic velocity. Therefore, uncharacteristic changes in the pulse velocity in these types of materials are due to defects, such as cracks or voids, which either delay or accelerate the received signal.

In nonhomogeneous materials, acoustic velocity varies locally due to natural changes in the microstructure such as grain orientation in wood. Although nonhomogeneous materials do not have a constant acoustic velocity, an average acoustic velocity can be obtained, for instance, for a given wood grain direction in a given specimen. A deviation from the average acoustic velocity greater than the deviations caused by the nonhomogeneity of the material itself signifies an "uncharacteristic" change in pulse velocity and, therefore, material properties. Use of ultrasonics is based on relating the uncharacteristic sonic signal to the condition of the structure.

Low frequency ultrasonic inspection of nonhomogeneous materials (wood) uses two transducers in a through-transmission mode, with one transducer acting as the transmitter and the other as a receiver. In contrast, high frequency ultrasonic inspection of homogeneous materials (metals) uses one transducer that acts as both transmitter and receiver in a pulse echo mode.

In initial low frequency ultrasonic laboratory tests signals from a solid specimen were compared to signals from a specimen with a known amount of cross-sectional wood loss. The laboratory test procedures, data analysis and test results are explained in detail in Reference 7. The laboratory evaluation of direct and indirect ultrasonic inspection indicated the following:

1. Ultrasonic time-of-flight and attenuation measurements do not consistently correlate with voids smaller than 25% of the wood cross-section.

2. Direct time-of-flight measurements cannot detect water-filled voids (marine borer tunnels) because the acoustic velocity of wood across the grain is very close to that of the acoustic velocity of seawater (Figure 2).

3. A digital readout of the time-of-flight or transit time alone is not an accurate or reliable measure of cross-sectional wood loss with either direct or indirect transmission modes.

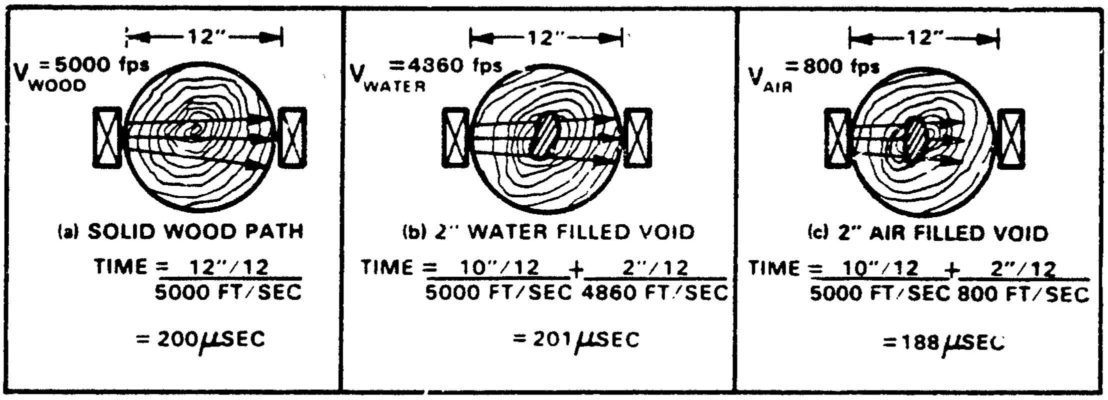


Figure 2. Direct transmission time-of-flight measurements through (a) solid wood, (b) solid wood with a 2-inch water filled void, and (c) solid wood with a 2-inch air filled void.

Although consistent correlation between the ultrasonic signal and the timber specimen had not been identified, further testing was required to determine what, if any, inspection capability existed. In particular, the accuracy and reliability of using ultrasonics for the inspection of timber waterfront structures must be determined. Based upon the laboratory test results the following recommendations were made:

1. Utilization of timber specimens with increasing known amounts of damage or wood loss to identify the minimum amount of damage detectable.

2. Incorporation of appropriate state-of-the-art data processing techniques to correlate digitized acoustic data to the condition of the timber.

3. Evaluation of ultrasonic parameters besides time-of-flight and peak-to-peak values.

4. Utilization of multiple transducers to show relative changes in the acoustic signal at adjacent locations.

ASSESSMENT OF POTENTIAL TIMBER NDT TECHNIQUES

In light of the problems encountered during the initial laboratory evaluation of ultrasonic inspection of timber piling, a study was conducted to identify new alternative techniques. A contract was awarded to Southwest Research Institute (SWRI), San Antonio, Tex., to evaluate existing and assess new NDT techniques for use by Navy divers (Ref 8). Potential NDT techniques were analyzed to determine feasibility and to predict performance capabilities and characteristics. The most promising techniques were then tested in the laboratory to demonstrate their feasibility.

From the results of the laboratory experiments and feasibility study conducted in seawater on small-scale wooden models with simulated marine borer damage along the grain, the contractor determined that the following six techniques were technically feasible:

- indirect ultrasonic testing
- impact testing
- X-ray tomography
- real time X-ray imaging
- acoustic emission
- dielectric measurement

Each of the six potential timber inspection techniques are discussed below.

Indirect Ultrasonic Analysis

SWRI evaluated this technique using essentially the same equipment as during the laboratory tests at NCEL. Two 50-kHz transducers, separated a distance of 18 inches in the axial direction, generated compressional

waves along the wood grain of timber specimens. Axial damage was simulated by cutting slots in wood blocks of various depths. Laboratory tests were conducted on wood blocks with slots equal to 0, 25, 50, 75, and 100% of the block thickness. The blocks were submerged in seawater.

Measurements of the RMS (root-mean-square) of the received ultrasonic signal were taken between two fixed times. An increase in the attenuation of the acoustic waves was expected with an increase in slot depth because of the impedance mismatch between water and wood in the axial direction. It was also expected that a portion of the wave energy would be delayed in time. Test results, summarized in Table 2, show a decrease in RMS amplitude with an increase in slot depth.

However, the decrease in RMS is not linearly related to the increase in damage. SWRI concluded "that the RMS of the transmitted signal between two fixed points in the time window decreases with an increase in slot depth, but there is no consistent relationship between slot depth and RMS amplitude."

Table 2. RMS Amplitude of Ultrasonic Signals for Various Slot Depths

[The transducers are placed on the opposite side of the slots.]

Slot Depth (%) (3.5 in.)	Signal Amplitude Millivolt RMS
0	113.8
25	20.02
50	17.5
75	5.0
100	2.8

Impact Analysis

The impact/resonance technique evaluated by SWRI during the contract differed from the technique evaluated at NCEL. SWRI's impact resonance tests were to determine the effect that axial holes in a wood pole had on vibration damping. In the SWRI tests, two accelerometers were placed on one side of a wood pole with axial holes simulating borer damage drilled into one end. The damping of vibrations generated by an impact located diametrically opposite each of the accelerometers was evaluated from the frequency response of the accelerometer output. No difference in modal frequencies between "solid" and "damaged" wood was noticed.

The impact testing technique evaluated at NCEL is an extension of the hammer sounding technique currently used by inspection divers in the field. By striking a piling with a hammer and listening to the quality or tone of the acoustic response, a diver can tell if there is extensive internal damage. After discussions with several experts in the wood and

lumber NDT industry, it appeared that, potentially, a technique could be developed for correlating changes in the frequency spectrum of impact-generated acoustic signals with the amount of cross-sectional wood loss in marine pilings. The NCEL impact testing technique is more thoroughly discussed in the IMPACT TESTING section of this report.

X-ray Tomography

Computerized axial tomography (CAT) systems currently used in the medical fields for imaging and diagnostics use a photon source and a bank of receivers. With this system a two-dimensional map of the cross-section of a specimen is reconstructed, using mathematical algorithms and data obtained from measuring the adsorption of the gamma rays transmitted through the material. The use of X-ray tomography in CAT scanners for inspection has been documented widely in the literature. Scientific Measurement Systems (SMS) of Austin, Tex., developed a CAT scanner to investigate preservative penetration in wood poles. Limited laboratory tests were conducted by SMS using their CAT system on sections of timber pilings with simulated marine borer holes drilled in them. The piling sections were submerged in water, but the holes were filled with air and the CAT system was completely dry. A CAT system has never been used underwater to date.

In a simulation study under contract to NCEL, AMETEK Offshore Research and Engineering Division, Santa Barbara, Calif., showed that X-ray tomography is feasible for detecting water-filled cavities in wood when at least a 0.5% density difference between wood and water is assumed (Ref 9). AMETEK also developed a conceptual design for an underwater computerized tomography inspection system (see Ref 10).

The work performed by SMS, AMETEK and SWRI indicated that an underwater computerized axial tomography system is technically feasible. However, definition of the packaging and operational requirements for a CAT system for effective use in a waterfront environment is needed.

Real Time X-ray Imaging

The real time X-ray imaging technique, which is based on X-ray radiography, has been used to determine the internal condition of living trees (Ref 11). However, no work has been done on inspecting borer-damaged wood piles, particularly under water; therefore, because of the great effort necessary to develop this technique, it was determined to be beyond the scope of the contract.

Acoustic Emission

SWRI evaluated an acoustic emission technique in the laboratory as part of the timber NDT assessment contract; it is based on the belief that a bending load applied to a wooden pile would produce sufficient stress to break wood fibers where the piling was weakened by the tunneling activity of marine borers. Also anticipated was that a higher acoustic emission (AE) count would result for an equivalent load from a pile damaged by marine borers than from an undamaged pile.

In the SWRI laboratory tests, three timber piles with varying amounts of wood removed were submerged in water and loaded in a three-point bending configuration. Good correlation between the AE counts and loss of cross section was observed. A sensor submerged in water was found more sensitive in AE detection than a sensor mounted directly on the piling. However, because of the high ambient noise level in most harbor environments, it was questionable whether or not the acoustic emission from wood piling could be detected. SWRI proposed subtracting the background noise from the AE rate to obtain the AE rate alone. Yet, based upon work with the passive sonic testing technique, distinguishing AE counts in a noisy harbor environment is still considered unlikely.

Dielectric Measurement

In this technique the change in the dielectric constant of a timber pile is measured and compared to the amount of wood and water-filled marine borer tunnels. Damage is indicated by the change in capacitance of a wood pile between two conducting plates. For the SWRI tests a flat plate capacitor was built by placing two copper plates on opposing sides of a wood pole. According to theory, the dielectric constant of the piling should increase with an increase in volume fraction of water caused by borer tunnels. Results showed a consistent increase in the dielectric constant with an increase in loss of cross section.

In these tests, a pair of copper foils, used as electrodes, must create a watertight fit around the pile: excluding all water between the copper foils and a saturated wood piling in the field does not appear feasible at this time. Therefore, NCEL decided not to pursue this technique further.

EVALUATION OF TIMBER INSPECTION TECHNIQUES

Based upon the contract results from SWRI, three of the six originally recommended techniques were selected for further evaluation at NCEL: X-ray tomography, indirect ultrasonic testing, and impact testing.

TOMOGRAPHY

The technique that holds the greatest potential for satisfying the accuracy requirements (Ref 1) for the detection of hidden defects in timber to this date is the CAT. Tomography, a radiographic technique, differs from a conventional radiograph in that it appears to be a cross-section photograph of the inspected object, taken as if the object had been sliced in a plane. A conventional radiograph appears as a shadow of the interior structure of the specimen. A tomograph is reconstructed from a set of projections of the specimen taken through that slice plane (Figure 3). Each projection is representative of the relative density, as a function of the angle through the slice plane, at each viewing position. The tomograph allows detailed visualization of the interior of the specimen (Figure 4).

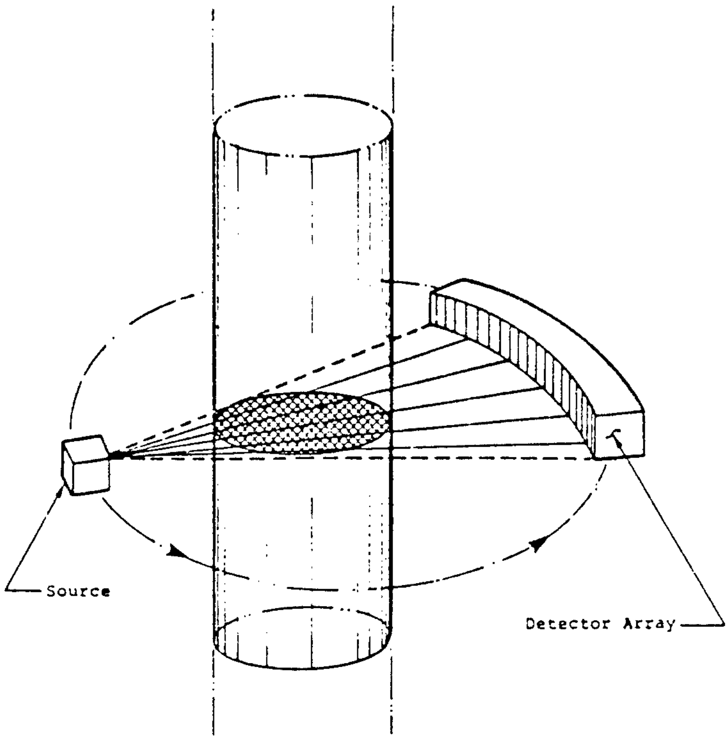


Figure 3. Tomographic scanning process.

In the final contract report from AMETEK Offshore Research and Engineering Division (Ref 9), the feasibility of developing a CAT system capable of operating in an underwater environment was documented. Underwater application of tomography is technically feasible. To minimize development risks, it was determined that a specialized system should be designed specifically for inspecting submerged timber structures rather than modifying an existing laboratory or "dry" CAT system. Results of the detailed analyses of the conceptual design, system performance, operational scenarios, and identification of critical issues for underwater CAT inspection of wood pier pilings can be found in References 9 and 10. The proposed prototype CAT system, inspection criteria for the CAT system, and scan time considerations are discussed briefly below.

The prototype CAT design consists of four basic subsystems shown in the block diagram of Figure 5. The scanner subsystem is composed of the source, detectors, and the necessary support and enclosures for underwater use. The telemetry subsystem consists of the electronic leads necessary to connect the scanner subsystem to the data acquisition and control subsystem. The raw data acquired at each incremental angle of rotation are formed into a matrix by the data acquisition and system control subsystem. The data conditioning, reconstruction, and display subsystem consists of the computer algorithms and the associated hardware required to reconstruct the tomogram from the data collected.

Figure 4. Tomograph of deteriorated timber utility pole.

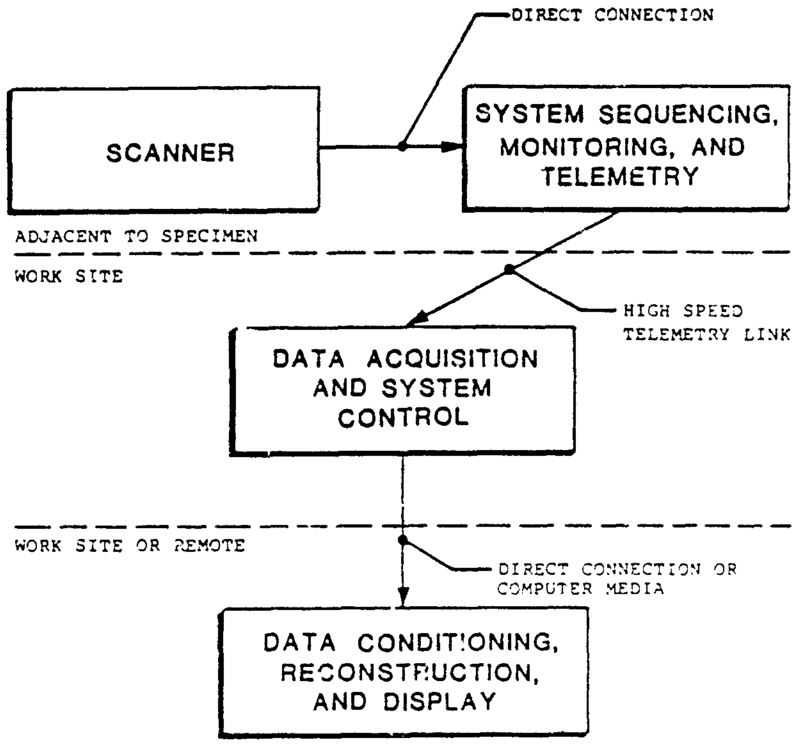


Figure 5. Functional block diagram of Computerized Axial Tomography System.

The inspection criteria for the scanner design was established based on the maximum diameter of wood pilings (18 inches), minimum internal flaw size desired to be detected (12.7 mm), capabilities of the present state-of-the-art detectors, and use of Iridium as the isotope source. The inspection criteria for wood under water are as follows: (1) the density resolution (Δp), 0.5%, and (2) spatial (width) resolution 6 mm $< \Delta w <$ 12 mm.

The scan time depends on the specimen thickness (w), spatial resolution (Δw) and density resolution (Δp). With a 18-inch wood piling and an Iridium source, the minimum scan times in minutes are based on detecting internal and external damage. Since damage to wood structures is primarily due to biological attack, the detection criteria are based on the size of the organism. The average size of shipworms (these cause interior damage) would equate in tomographic parameters to a spatial resolution (Δw) of 1/2 inch (12.7 mm) as the minimum spatial requirement. To detect the damage caused by the Woodgribble (most severe in terms of small spatial resolutions), a 1/8-inch (3-mm) spatial resolution would be necessary. Since the damage caused by the Woodgribble is exterior, the spatial resolution was eased.

Accuracy With Respect to Damage (%)		Spacial Width, Δw (mm)	Minimum Scan Time (min)
Internal	External		
0.01	0.03	6	12.0
0.02	0.05	8	5.1
0.03	0.1	12	1.5

A brief summary of the underwater CAT system requirements for inspection of wood pilings follows.

- Fan Beam Full Illumination Scanner
- 78.3 Fan Angle
- Center of Rotation (COR) - centered detector array configuration
- Iridium Source
- 200 Curie Intensity
- 127 Detector Array

INDIRECT ULTRASONIC TESTING

Commercial Demonstration

A demonstration of commercial ultrasonic inspection capabilities by Agi and Associates was completed in 1982. Timber piers known to suffer from marine borer damage (San Diego, Calif., and Pearl Harbor, Hawaii) were inspected.

The basic components of the ultrasonic system used by Agi and Associates are: two magnetostrictive transducers, a single trigger and timing unit, a transducer drive, the received signal and amplification system, and a meter presentation of the received signal. The transducers operate at approximately 30 kHz and transmit over a fixed distance of about 3 feet. A rigid framework maintains spacing between the transducers as they are moved along the length of the pile (Ref 12).

The testing crew consists of two persons. One using scuba equipment to scan the entire pile from the water surface to the mudline with the sonic probe and a second on the surface to maintain a continuous record of the sonic and visual data.

The initial reading is taken at a known solid region of the pile (usually above the waterline) and used as the standard reference. The analog display in the surface unit provides a direct readout of the percentage of undamaged wood remaining in the pile cross section (compared

to the initial reference). Where damage is indicated, the diver provides close visual observations concerning the type and location of damage, eccentricity of voids and other pertinent information. These observations are relayed to the surface technician through a telephone link.

Several of the inspected pilings were removed, sectioned, and crushed to compare inspection results to actual cross-sectional area and remaining strength. This study was designed to: evaluate the inspection test results obtained with the ultrasonic test equipment; compare the ultrasonic inspection results with visual inspection results; and compare ultrasonic and visual inspection results with established accuracy requirements. Reference 12 presents a detailed description of the capabilities demonstration and discussion of the results. A brief summary of the results are stated as follows:

- The Agi and Associates ultrasonic inspection equipment can detect both external and internal timber damage.

- The ultrasonic inspection overestimated the actual damage in San Diego by an average of 16% and in Hawaii by 18%. Visual inspection of the same piles in Hawaii underestimated damage by 13%.

- The variance for both the visual and ultrasonic inspections was very high. The standard deviation ranged from 12.1 to a high of 21.9 for the ultrasonic inspections and 13.3 to 16.3 for the visual inspection results. Since the variance is directly related to the precision of the measurement of cross-sectional area for any single pile it should be much lower to meet the accuracy requirement of 20 to 25% given in Reference 1. For 95% of the measurements to fall within the accuracy specification, the standard deviation associated with the measurement of cross sectional area must be approximately 6% or less. From this standpoint, neither inspection technique meets the inspection criteria defined in Reference 1.

NCEL Ultrasonic Laboratory Testing

The reason for pursuing indirect ultrasonic testing at NCEL was based on three points:

- Previous ultrasonic tests conducted at NCEL (Ref 7) showed that although a consistent correlation between the ultrasonic signal and the wood specimen condition could not be identified, alternative ultrasonic parameters had not yet been investigated. Further study was warranted.

- The results from the SWRI contract indicated that indirect ultrasonic testing is a feasible inspection technique. Positive results were achieved when the RMS of the ultrasonic signal was compared to the amount of wood lost. The signal RMS consistently decreased with an increase in wood damage.

- The Agi and Associates ultrasonic test demonstration proved that ultrasonic equipment is not just a potential technique; it has been satisfying a current need. Although the accuracy is less than the predetermined requirement, ultrasonic inspection reveals information about the interior, rather than only the exterior, of a timber pile, as with visual inspection.

The low frequency ultrasonic equipment used by NCEL is commercially available from James Electronics, Inc., Chicago, Ill. This ultrasonic equipment is used routinely during field inspections of lumber, utility poles, and concrete terrestrial structures. The entire system (Figure 6) consists of two lead-zirconate-titanate ceramic piezoelectric transducers mounted in stainless steel cases; a portable ultrasonic digital readout meter (called the V-meter) equipped with a factory-installed adapter to permit direct readout on an oscilloscope; and an analog display unit that converts digital transit time measurements into analog form. Initial ultrasonic tests determined that transit time measurements were not a reliable or accurate measure of cross-sectional wood loss; consequently, the analog display unit that converts digital transit time measurements to analog form was not employed. A schematic of the ultrasonic test system configuration is shown in Figure 7.

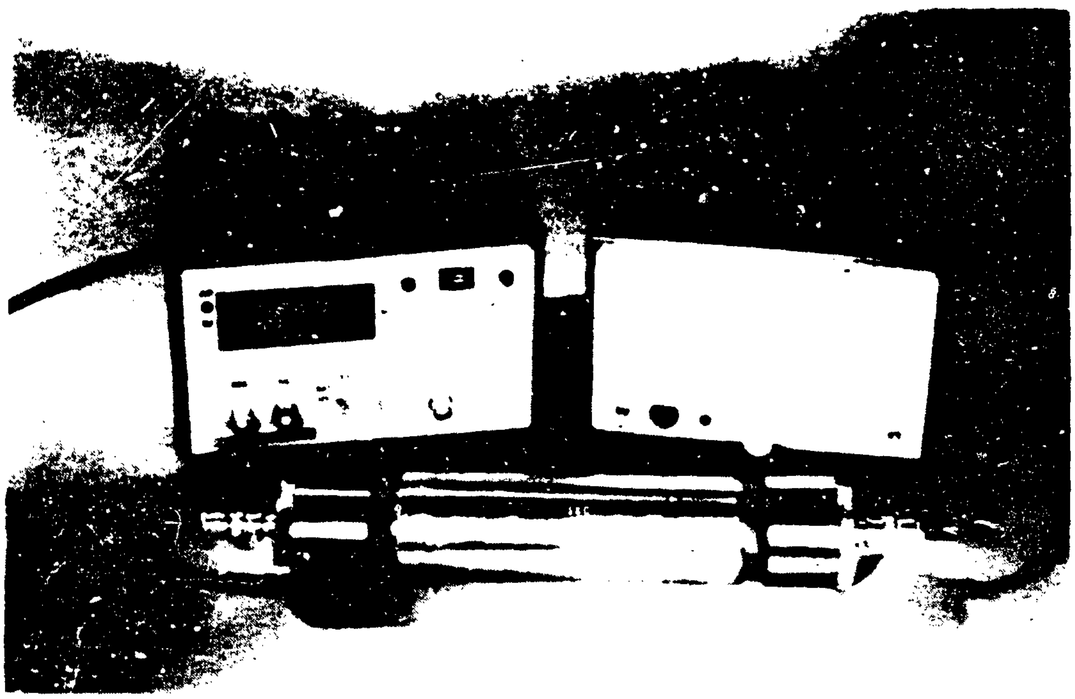


Figure 6. Transducers, ultrasonic v-meter and analog display unit.

The ultrasonic parameter that indicated the highest potential for correlation to the amount of cross-sectional wood loss was the RMS amplitude of the ultrasonic signal received. A computer program to calculate this value was written for the Tektronix 4052 computer.

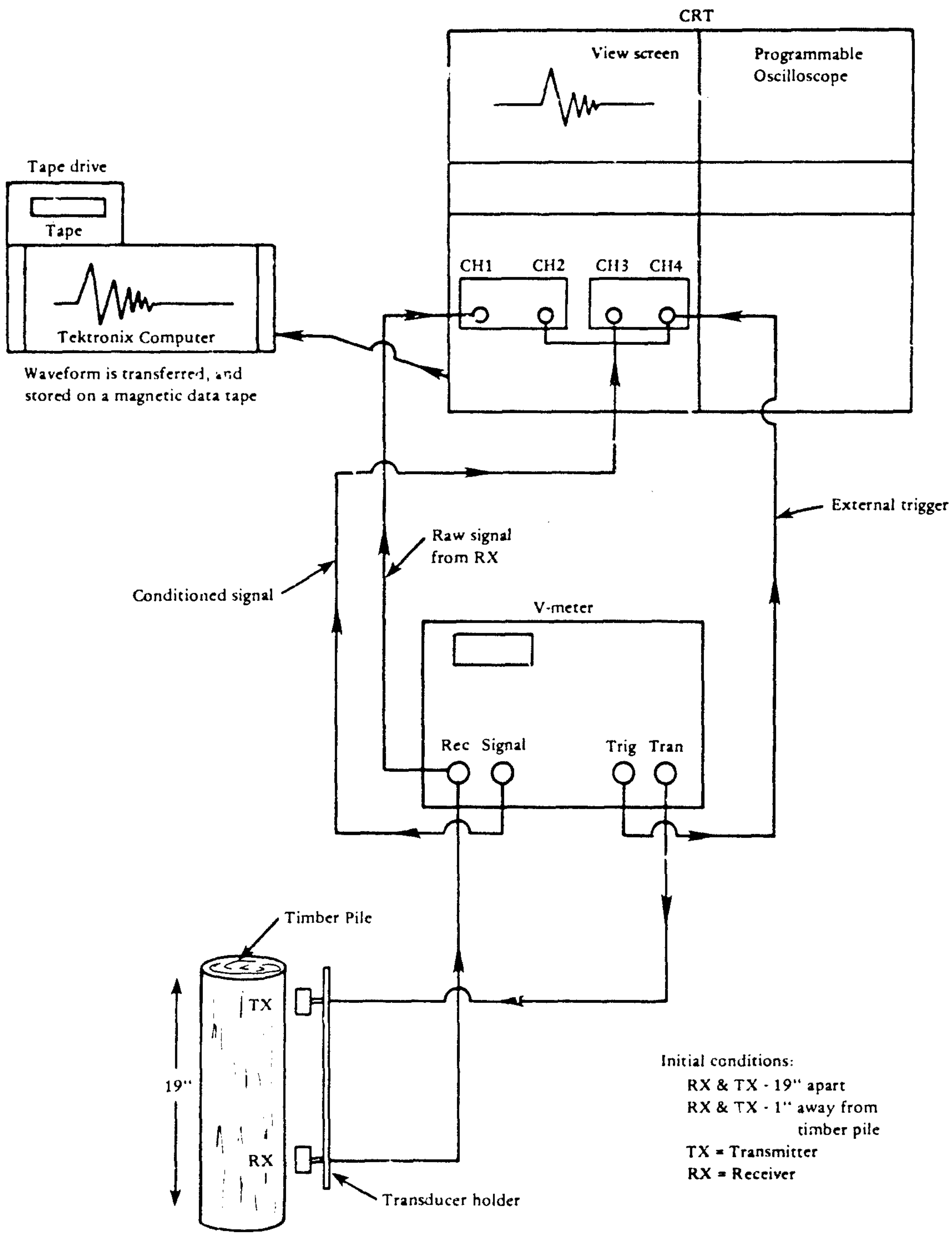


Figure 7. Schematic of ultrasonic test system configuration.

The transducers operate at a frequency of 54 kHz and were waterproofed for underwater use. Two holders were designed and fabricated to align and secure the transducers in the correct orientation for direct and indirect transmission (Figure 8). Direct transmission requires that the transducers be placed on opposite sides of the element. Indirect transmission requires that the transducers be placed on the same side of the specimen (Figure 9). Both frameworks maintain the transducers a fixed distance apart. In recent ultrasonic tests, only the indirect transducer holder was used because the acoustic velocity of the sonic signal across the wood grain is so similar to that across water.*

Laboratory Test Preparations. Prior to each series of laboratory tests, the following preparations were made:

- The circumference of the test pile was divided and marked into four quadrants.

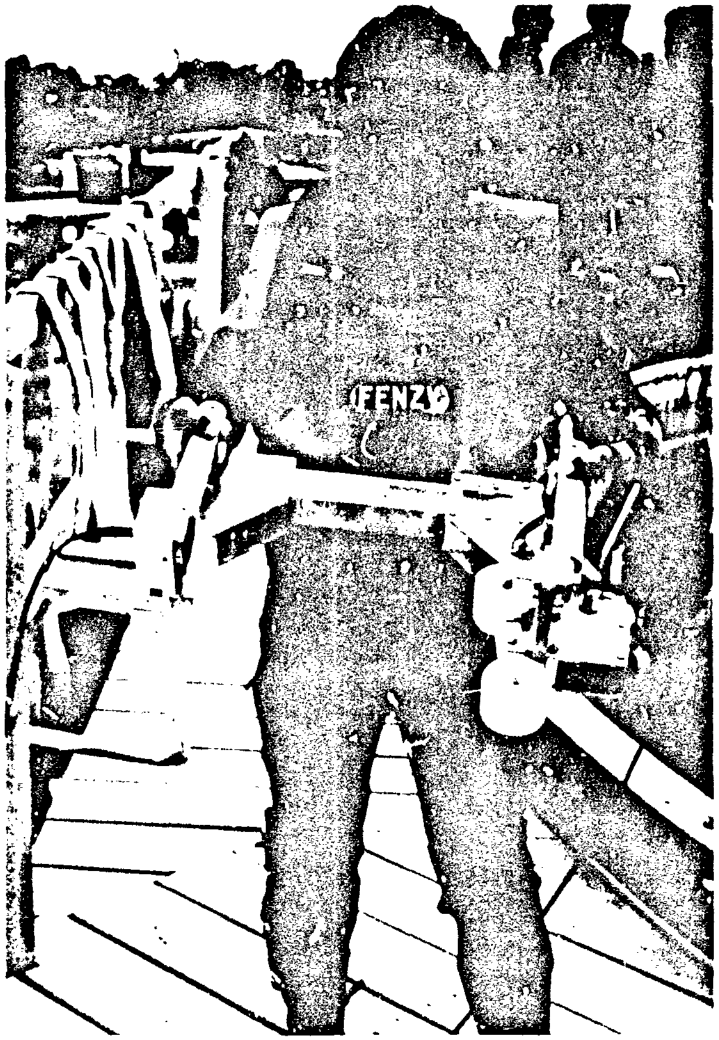
- The length of the pile was divided and marked into 3- to 6-inch increments depending on the amount of damage.

- A drawing was made of the test pile showing any external damage, internal damage, or other pertinent information (damage measurements, pile diameter, etc.).

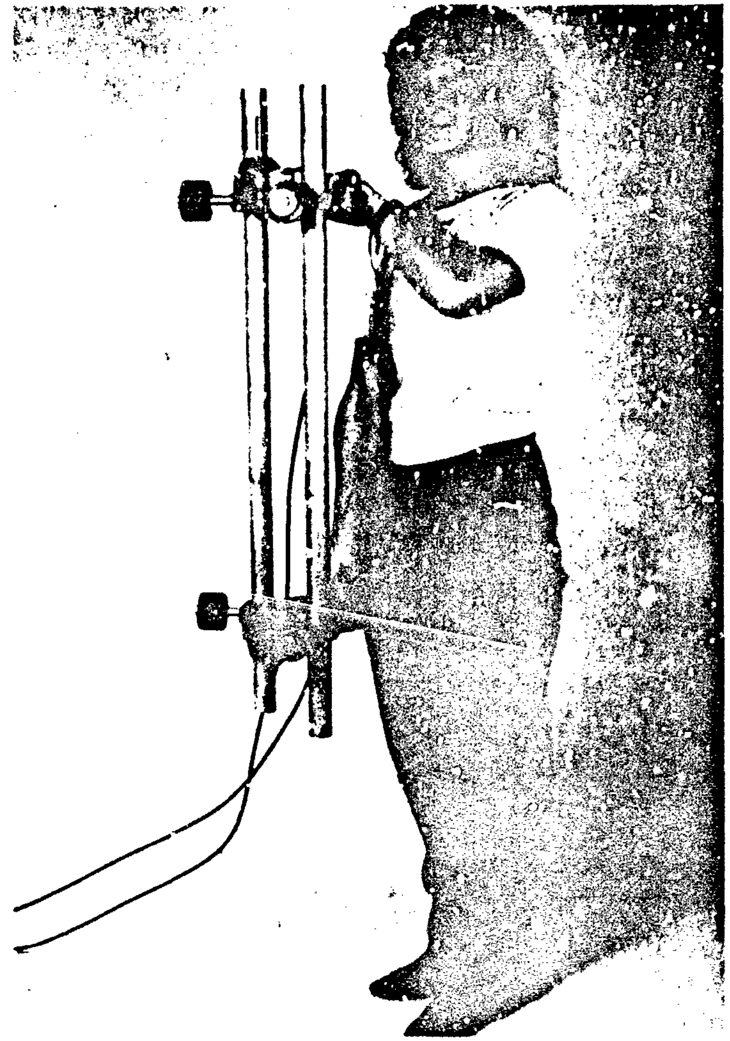
Description of Piles. Indirect ultrasonic laboratory tests were conducted on piles with simulated and actual biological damage. Piles with actual borer damage were obtained from San Diego and Hawaii (see Figure 10). Those piles with actual borer damage were numbered: 5x, 4x1, 8335D and 8323E. The test pile with simulated borer damage was referred to as the "standard" pile. Initially, the standard pile had multiple small diameter (3/8-inch) holes drilled 21 inches deep in two quadrants. However, these holes became enlarged and blocked with debris after a relatively short period of time.

Procedures. Following initial preparations, the transducer holder (containing the TX and RX transducers) was placed against the timber pile in the desired location. The transducer holder is designed to allow the arms to be adjusted to the pile diameter. Although the transducer holder is placed directly against the pile, the transducers themselves remain approximately 1 inch away. Consistency between each series of tests was achieved by beginning each test at the first marked line in quadrant 1 and proceeding down the pile to the last line for each of the quadrants.

*This was explained previously in the section on Low Frequency Ultrasonics and is shown in Figure 2.

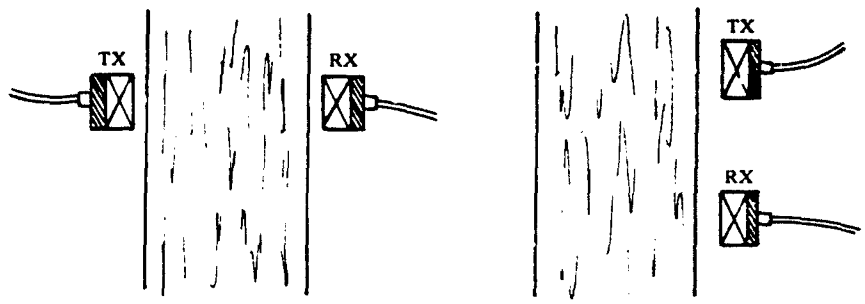


(a) Direct.



(b) Indirect.

Figure 8. Indirect and direct transducer holders.



(a) Direct Transmission (b) Indirect Transmission

Figure 9. Two methods of ultrasonic through transmission.

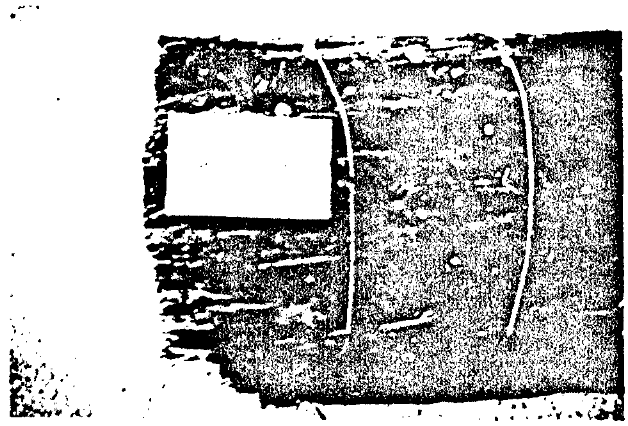
The number of ultrasonic signal readings taken along each individual pile was dependent on the separation length of the transducers and the length of the pile. However, the transducers were held at a fixed distance of 19 inches in the transducer holder during all laboratory tests. Consequently, the number of readings taken was dependent only on pile length. The maximum number of readings (100) was taken on the standard pile. Approximately 20 readings were taken for each of test piles 5x, 4x1, 8335D, and 8323E. Every reading was repeated to evaluate reproducibility of test results. If discrepancies between an initial and second waveform reading were observed, a third reading (or more, if necessary) was taken in the same location.

The data recorded for each series of tests included the following information:

- digitized ultrasonic signal waveform
- location of the transmitter and receiver
- description of the pile, including a sketch showing damage in test locations
- separation distance of the transducers
- distance between transducers and pile surface
- settings on the 7854 programmable oscilloscope
- time, date, and location of the test
- tape and file number
- any changes in test setup or execution
- comments, including noticeable changes in recorded waveforms

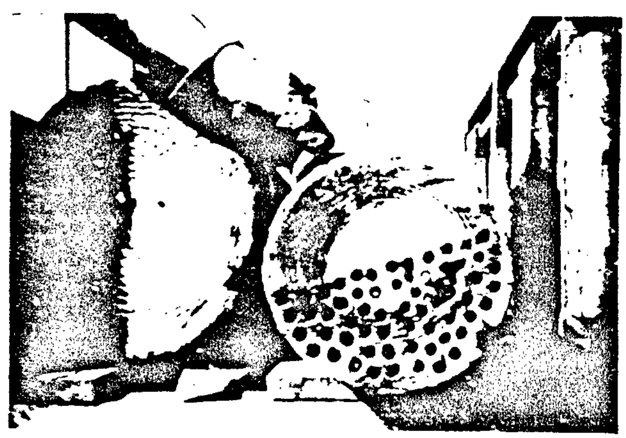
(a) Pile 4X1.

(b) Pile 5X.



(c) Pile 8335D.

(d) Pile 8323E.



(e) Standard pile.

Figure 10. Laboratory test piles.

Laboratory Test Results. Low frequency ultrasonic theory indicates that the strength of the signal picked up by the receiver will be stronger in solid wood than in damaged wood. The transmitter sends sonic waves into and down the grain of the wood. The receiver picks up the signal and relays it to the oscilloscope, which measures the strength of the signal and its time of passage for the fixed distance in the wood. The amplitude of the digitized ultrasonic waveform received indicates the strength of the signal. As a result, the decrease in the RMS amplitude of the ultrasonic signal received is the parameter that holds the greatest potential for correlation with the amount of cross-sectional wood loss. The RMS is the square root of the mean of the squared amplitudes. The formula for calculating the RMS amplitude is as follows:

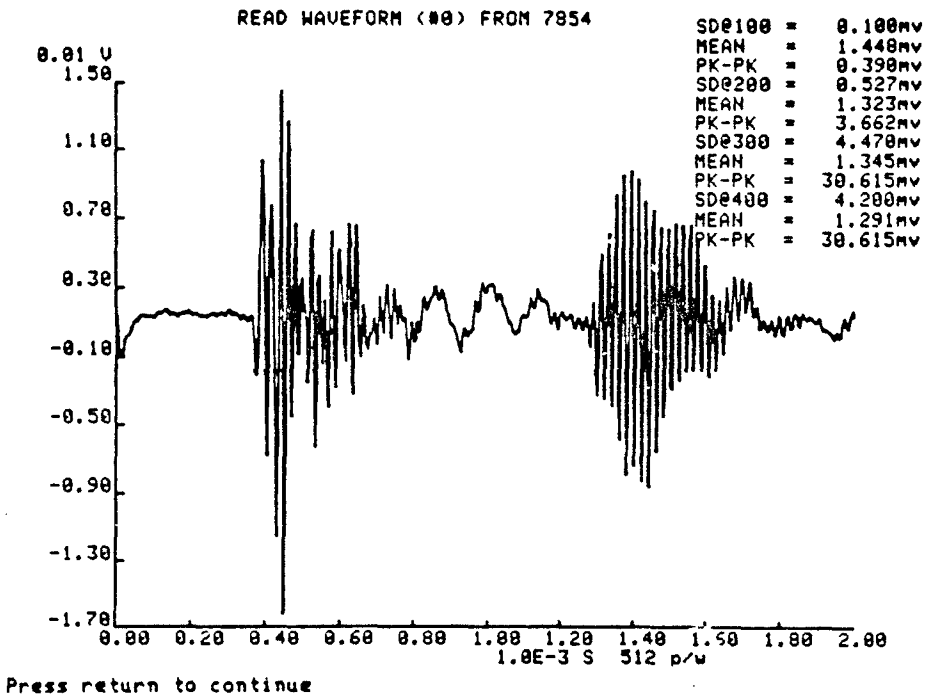
$$\text{RMS} = \left[\frac{\Sigma x_i^{\,2}}{N} \right]^{1/2}$$

After looking at the RMS amplitude of the ultrasonic signal for the various test piles, a large discrepancy was apparent between the RMS values for different timber piles. For example, the average RMS values for the standard pile were 1.4 to 2.2 mV, while the average RMS values for pile 5x were 14.5 to 15.0 mV. The DC level of the ultrasonic signal was shifting, seriously affecting the calculated RMS. To compare RMS values of the ultrasonic signals, a synchronized horizontal time base is required for identifying the wave amplitude components for attenuation measurement. However, to compensate for the irregular DC shift exhibited in all the ultrasonic signals, the standard deviation of the ultrasonic signal over a specific time period was determined. The formula used to calculate the standard deviation is shown below:

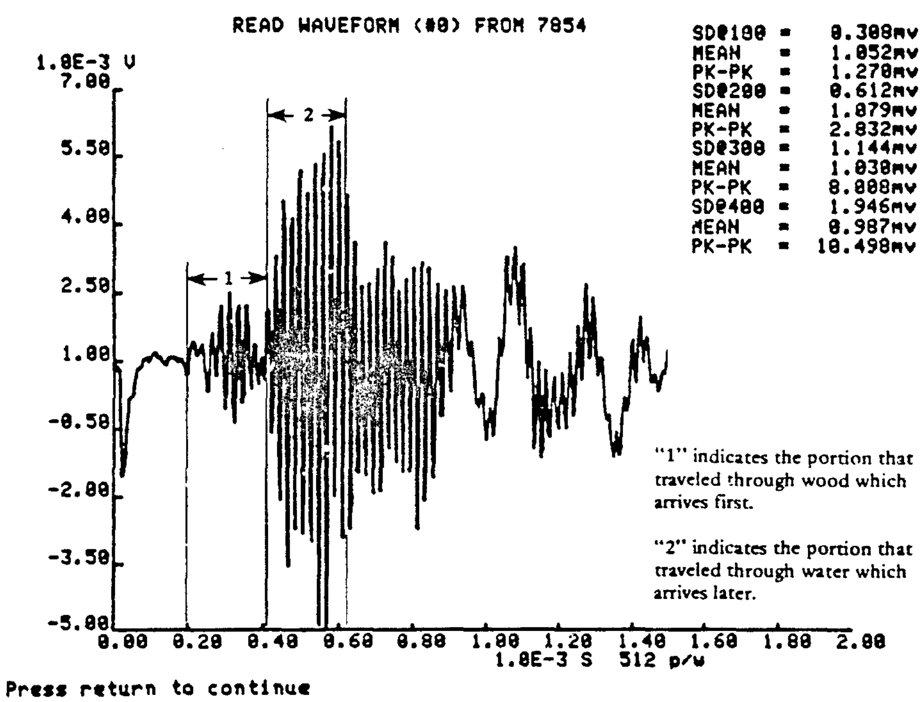
$$\text{Standard Deviation} = \left[\frac{\Sigma x_i^{\,2}}{N} - \left(\bar{x}\right)^2 \right]^{1/2}$$

The standard deviation creates a synchronized horizontal time base by subtracting the mean amplitude squared from the sum of squared ultrasonic signal amplitudes as shown. This eliminated the erroneous readings obtained from comparison of only the magnitude of the amplitudes (RMS).

Standard deviation, mean and largest peak to peak value were calculated over four different time domains of the ultrasonic signal. This signal was separated into discrete time frames or "bins" (100, 200, 300, and 400 µsec) to evaluate the difference in sound velocity between wood and water. Compressional sound waves travel in solid wood with a velocity of approximately 5,000 m/sec along the grain, whereas waves travel through seawater with a velocity of 1,500 m/sec. Figure 11 shows two ultrasonic received signals. A typical acoustic sound wave received after traveling only through water is shown in Figure 11a. In comparison, an ultrasonic signal received after traveling through a solid timber pile for the same path length or transducer separation of 22 inches is shown in Figure 11b. The smaller amplitude wave indicated by a "1" in the figure is the part of the acoustic signal that traveled through the



(a) Through seawater.



(b) Through wood.

Figure 11. Received ultrasonic signals.

wood. The amplitude and strength of this portion of the signal is affected by the internal condition of the timber pile. The part of the signal traveling through the water indicated by a "2" in the figure arrives later but with a larger amplitude.

The fixed distance between the transducers was set at 19 inches (0.483 meter) for laboratory tests. The travel time for the sonic signal to travel directly through the timber pile from the transmitter over the fixed distance to the receiver would be equal to 97 μsec (0.483 m ÷ 5,000 m/sec). Consequently, the first time frame of 100 μsec relies heavily on the arrival of only the ultrasonic signals traveling through sound wood. The travel time for the sonic signal to travel through a damaged pile section is influenced by the amount of water contained in the damaged area. If the damaged area were completely filled with water (e.g., from borer damage), then the time for the sonic signal to travel from the transmitter to the receiver would be 320 μsec (0.483 m ÷ 1,500 m/sec). Therefore, the ultrasonic signal contained in the 400 μsec bin is influenced mainly by the slower, larger amplitude waves traveling through water. The 200- and 300-μsec bins are intermediate time frames that include the waves traveling partially through water-filled voids and solid wood along with the stronger amplitude waves traveling only through water.

The location of the transducers was recorded using the quadrant number (Q) and the transmitter-to-receiver increment position (TX-RX). A data entry identified by Q1-2 RX1 TX8 means the ultrasonic signal was transmitted through the wood between quadrants 1 and 2 with the transmitter at the 8th marked line and the receiver at the 1st marked line. The distance between the marked lines varied for each test pile as explained previously.

After completing the laboratory ultrasonic and impact tests, the five laboratory test piles were sectioned and photographed. The photographs of the various sections for each pile were enlarged and the cross-sectional area was divided into quadrants. An example is shown in Figure 12. With the photographs and an engineering tool called a planimeter, the cross-sectional area remaining in each quadrant was calculated. Subtracting the remaining cross-sectional area from the total cross-sectional area gave the amount of cross-sectional area loss. Correlation between the amount of cross-sectional area loss in each quadrant and the standard deviation of the ultrasonic signal received in the respective quadrant was investigated.

Figure 13 shows the relationship between the cross-sectional wood loss of the standard pile and the standard deviation over four different bins of the ultrasonic signal. The best correlation between the standard deviation and the cross-sectional wood loss was found to be over the 100-μsec time bin (Figure 13). Standard deviation generally decreases with an increase in the percent of cross-sectional wood loss. It is apparent from the figure that the data collected contain discrepancies. Standard deviation (over 100 μsec) for a 17% cross-sectional wood loss is higher than standard deviation where a 9% cross-sectional wood loss exists. Repeated readings often varied in the same location. Signal variations that occur through a constant amount of cross-sectional loss are due to material changes in the structure and grain orientation of

the timber pile. Figure 13a shows a shift in signal strength measured by the standard deviation from 0.2 to 2.5 mV for a constant 0% cross-sectional area loss. These natural variations were verified when large or significant fluctuations in signal strength were measured in different quadrants of a completely solid pile (see Figure 14).

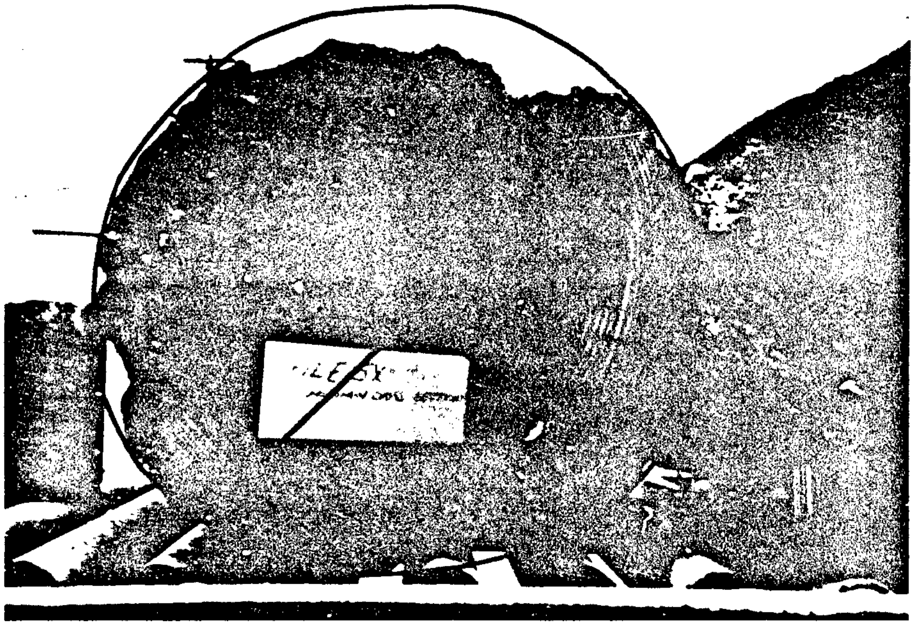
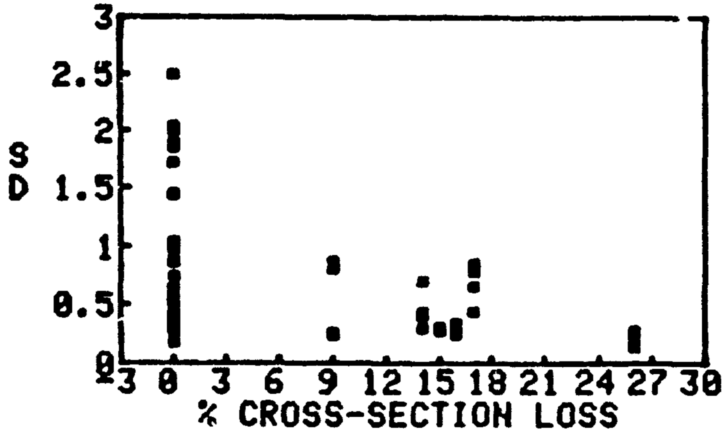


Figure 12. PILE 5X: Cross section divided into pie-shaped quadrants.

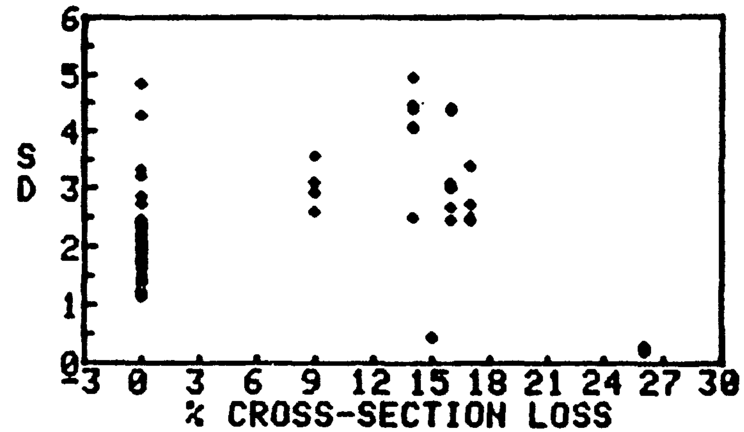
The relationship between the cross-sectional wood loss and the calculated standard deviation of the ultrasonic signal over the 100-μsec time increment for the test piles (standard, 5x, 4x1, and 8335D) is in Figure 15. As shown in Figure 13b the ultrasonic readings taken for pile 5x (Figure 15b) were unlike the standard pile. The steady decrease in standard deviation with an increase in cross-sectional wood loss of pile 5x is not as evident. The largest discrepancy exists in the region where 74% cross-sectional wood is lost. Standard deviation increases where a decrease is expected.

Again, readings vary significantly for a constant cross-sectional area loss. The plots of standard deviation versus the percent of cross-sectional wood loss for pile 4x1 and pile 8335D show a wide range of values with no consistent or significant decrease in standard deviation with cross-sectional wood loss.

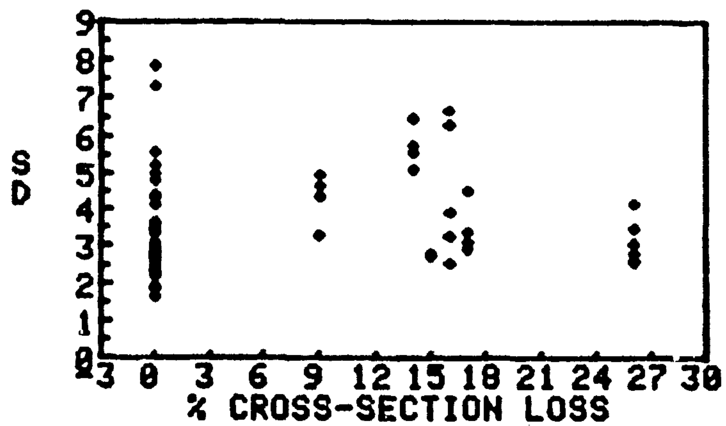
To clarify the extent of association between the percent of cross-sectional wood loss and standard deviation of the ultrasonic signal, a regression analysis was performed on the data collected for each pile. Regression deals with the prediction of one variable from its correlation with others. The two variables being correlated (percent cross-sectional area loss and standard deviation of the ultrasonic signal) are shown in graphic form in Figure 16.



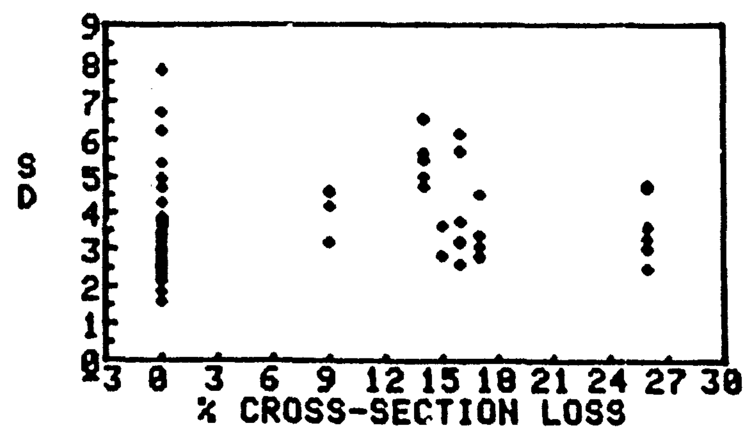
(a) 100 μsec



(b) 200 μsec

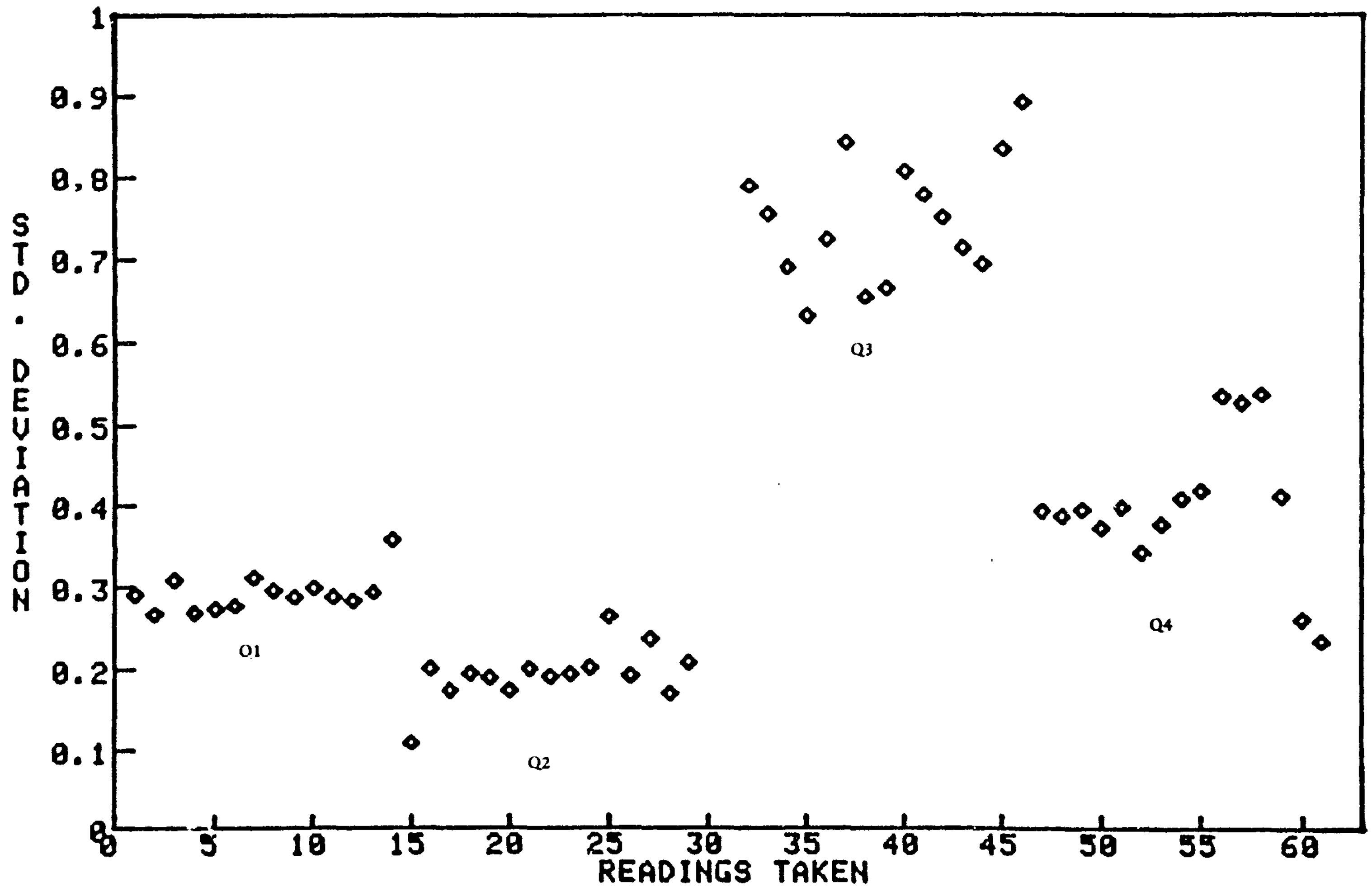


(c) 300 μsec



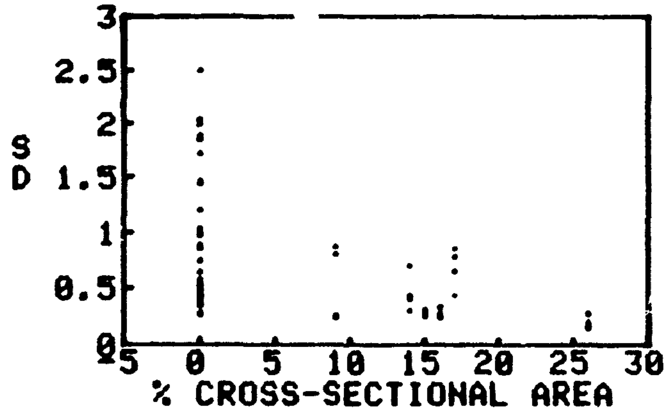
(d) 400 μsec

Figure 13. Standard deviation versus percent cross-sectional wood loss for the standard pile.

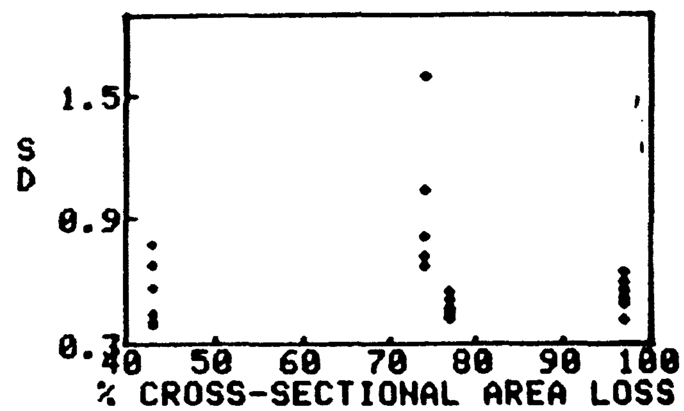


CHECK FOR REPEATABILITY (Q1,Q2,Q3,Q4)

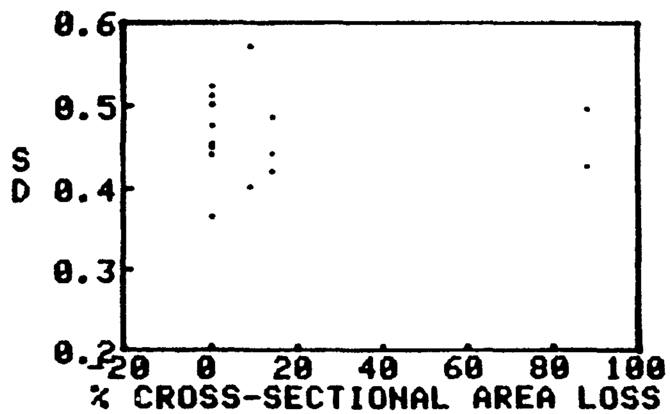
Figure 14. Variation in standard deviation (100 μsec) for a solid pile.



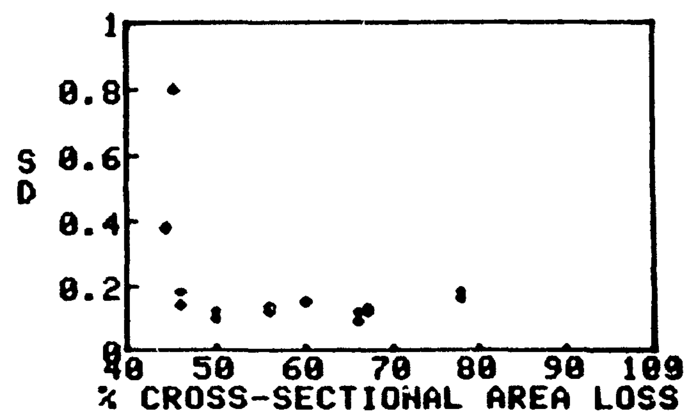
(a) Standard Pile



(b) Pile 5X



(c) Pile 4X1



(d) Pile 8335D

Figure 15. Standard deviation (100 μsec) versus percent cross-sectional wood loss for timber piles.

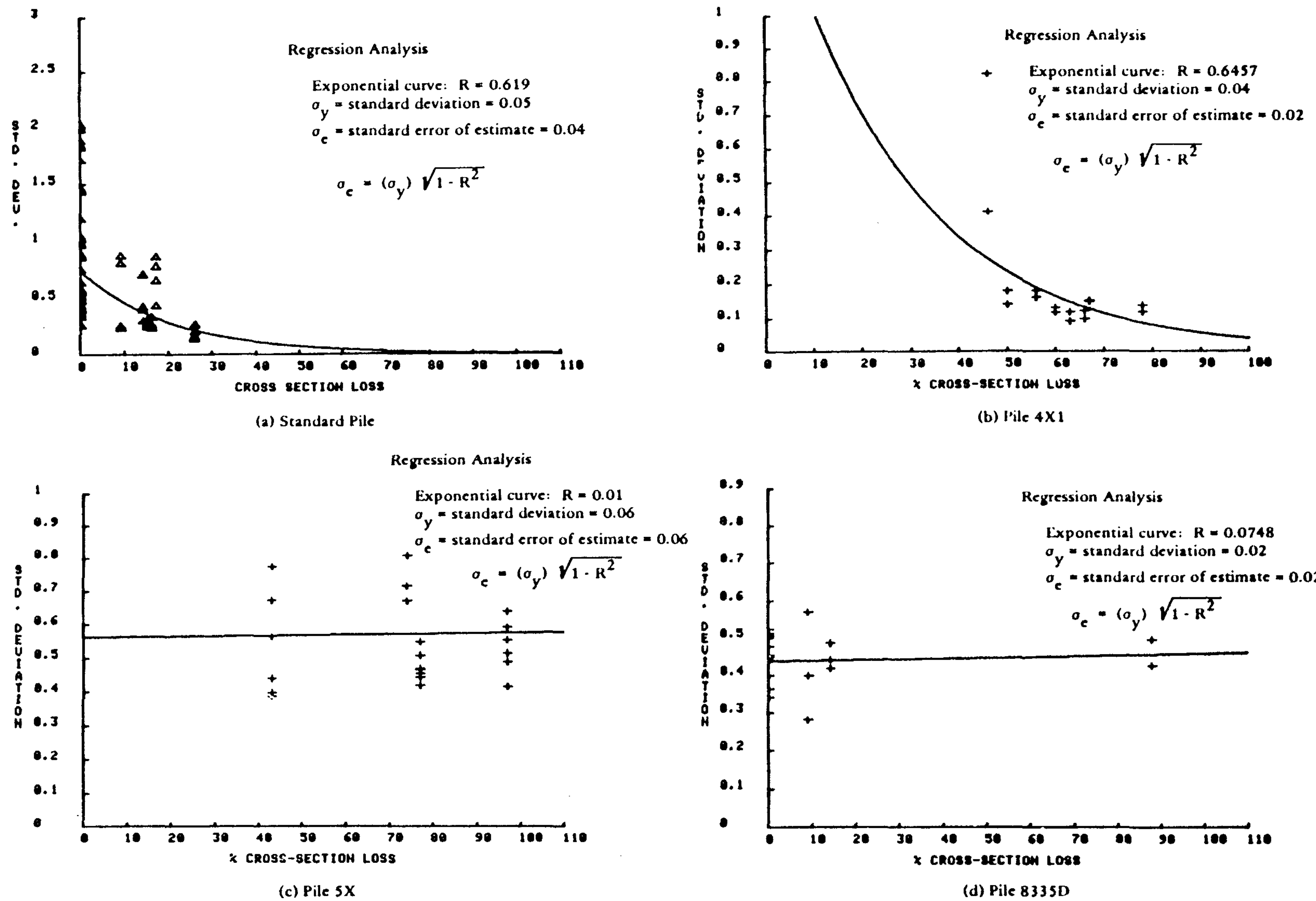


Figure 16. Regression analysis curves for laboratory test piles.

The curve of best fit was drawn through the data points. The best fit description relies on the statistical measure of the extent of the relationship between the two variables called the coefficient of correlation (R). A value of R = 1 indicates a perfect association or complete dependence of one variable upon another. The value of R is shown along with the curve chosen for each pile.

The curve of best fit will yield accurate estimates if the variation around it is small. The variation around the curve is called the standard error of estimate. Standard error of estimate was calculated and is also shown in Figure 16 with the respective curves for each test pile.

Because of the natural variability in materials such as wood, an absolute standard for all timber pilings and standard deviation of the received ultrasonic signal cannot be determined. Each pile tested has its own signature that defines the properties of that pile. During an inspection, an average standard deviation would have to be recalibrated on a solid section for each pile.

NCEL Ultrasonic Field Testing

In June 1982, NCEL installed seven timber pilings with various degrees of biological damage along the corrosion test pier located in Port Hueneme harbor in California. This pier is situated where marine borer populations and their activity are known to be great. These timber pilings were allowed to deteriorate further from biological attack for approximately 1 year. In July 1983, three of the seven installed pilings and one of the support piles for the corrosion pier were inspected by Navy divers. Two inspection techniques, ultrasonic and impact testing,* were employed.

For successful evaluation of any inspection technique, a range of biological damage was desired. First, the divers visually inspected the installed piles to locate the timber pile with the least, and the other with the most, obvious amount of damage. As expected, a new pile had the least amount of external damage. The ultrasonic tests were first conducted on the new pile (no. 8). Following the ultrasonic tests on the new pile, the Navy divers inspected three additional piles with various degrees of external damage.

The same equipment configuration as that in the ultrasonic laboratory tests was used (Figure 7); initial preparations were also similar. Variations were as follows: the length of the pile was divided and marked with a line into 1-foot increments instead of 3- to 6-inch increments; the external damage, internal damage, and any other pertinent information were recorded on video as well as in drawings; the separation distance between the transducers in the transducer holder was set at 22 inches instead of 19 inches; and the ultrasonic signal from the receiver was averaged 100 times to reduce the noise level.

Two divers and an engineer at the surface were employed during the actual testing. One diver used video equipment to examine the pile for damage in the area being tested and documented the actual test procedure.

*See IMPACT TESTING section for discussion of this technique.

The other diver placed the transducer holder directly against the pile in the designated regions of the pile. The engineer at the surface viewed the movements of the diver holding the transducer, observed any external damage pointed out by the diver with the video camera, and monitored the ultrasonic signal from the receiver shown on the cathode ray tube (CRT) screen.

Communication was from the surface engineer to the video-equipment diver. This allowed the engineer to inform the diver when a closer look at damage was desired and when a reading needed to be repeated; but with only one-way communication, the diver could not relay to the surface engineer any problems encountered or visual observations pertinent to the ultrasonic testing until after surfacing.

The diver operating the transducer holder traveled from the marked line at the waterline to the marked line at the mudline for each of the quadrants on each pile. During testing two readings to check repeatability were taken of each pile at 40 different locations. The data recorded for each series of tests included the same information described in Procedures of the NCEL Ultrasonic Laboratory Testing section of the report.

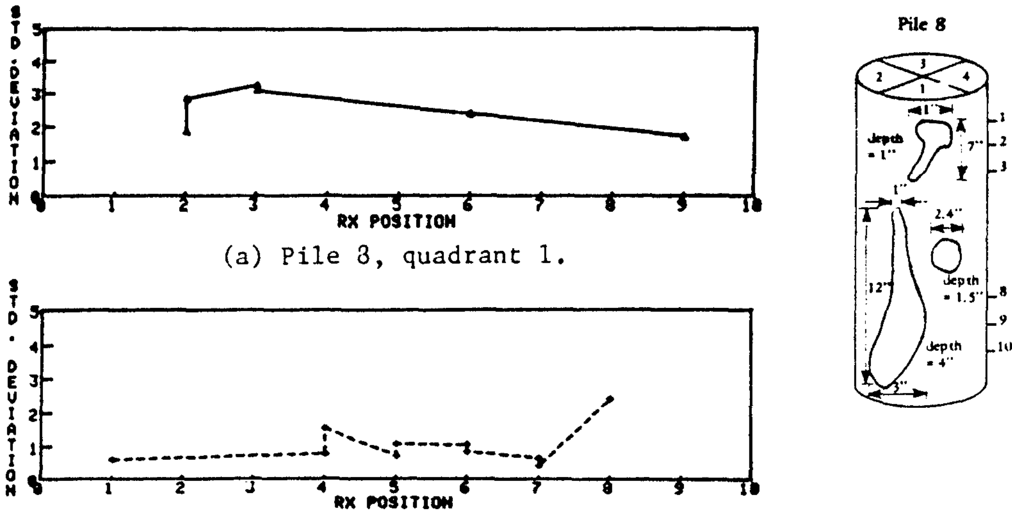
Field Test Results. Unlike the laboratory test piles, the harbor test piles were not sectioned to determine the percent of cross-sectional wood loss because these piles will remain in place for future inspection testing. Therefore, the ultrasonic equipment can be evaluated only on detection of external damage.

For the four (three damaged and one new) harbor test piles inspected, the regions of external damage were identified by combining visual, video, and photographic data. Extent of the external damage (including length, width, and depth of damage) was also determined. After location and extent of damage for each pile were established, standard deviation of the ultrasonic signal at these locations was evaluated. Based on ultrasonic laboratory test results, standard deviation of the ultrasonic received signal over the 100-μsec time interval held the greatest potential for correlation to the amount of cross-sectional wood loss. Thus, only standard deviation of the ultrasonic signal received over the time frame of 100 μsec was investigated.

Figures 17 through 19 give the ultrasonic field data collected at and near the damaged regions. Regions of external damage were compared to regions of no external damage. The location and dimensions of the external damage are also shown in Figures 17 through 19, although the damage is not to scale. This comparison showed the change in the standard deviation with external damage; however, the amount of external damage on all the piles inspected in the harbor was minimal (less than 15% cross-sectional loss).

Figure 17 shows the relationship between the external damage of pile 8 tested in the harbor and the standard deviation of the ultrasonic signal received over 100 μsec. Quadrants 1 and 2 of pile no. 8 were analyzed; damage in quadrant 1 is substantial compared to that in quadrant 2. Length and depth of damage are relevant to its detection using ultrasonics. Therefore, the results in quadrant 1 (Figure 17a) show a definite decrease in the standard deviation in regions where

external damage is shown. The standard deviation decreases from approximately 3 to 2.5 mV when the ultrasonic transducers are positioned closer to the damage. When the transducers are placed directly over the damage, the standard deviation decreases to approximately 1.7 mV. The ultrasonic readings taken in quadrant 2 fluctuate slightly without regard to the damage exhibited.



(a) Pile 8, quadrant 1.

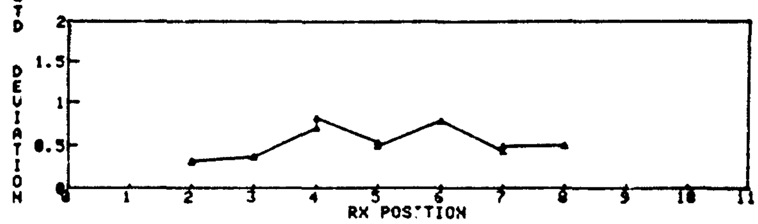
(b) Pile 8, quadrant 2.

Figure 17. Ultrasonic field tests: standard deviation (100 μsec) versus position of receiver (RX) for Pile No. 8.

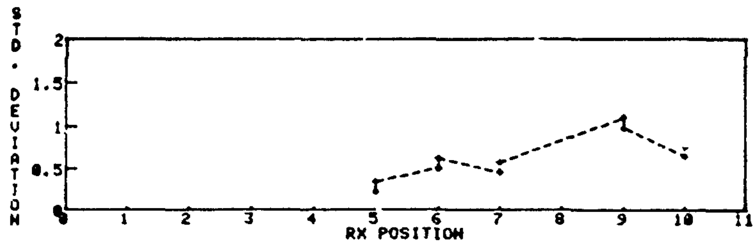
Figure 18 gives the standard deviation readings over 100 μsec for pile no. 5. Again, two quadrants were evaluated. The greatest amount of damage in quadrant 2 (Figure 18a) is shown between line markings 3 to 5. As shown, the standard deviation is low at lines 3 and 5. Quadrant 3 (Figure 18b) has minimal damage with the greatest damage depth being 0.6 inch. In the damaged region of quadrant 3, the standard deviation fluctuates from approximately 0.2 to 0.6 mV. In comparison, the standard deviation in the solid region ranges from 0.6 to 1.1 mV.

The external damage shown on pile no. 1 is almost nonexistent (Figure 19a). Yet, the standard deviation varies from approximately 1.8 to 20.1 mV. This fluctuation in the standard deviation is observed where no change in the pile condition is shown.

Figure 19b shows the change in the standard deviation with the external damage over 100 μsec for the Support Pile. The standard deviation decreased from a range of approximately 0.7 to 1.8 mV in the solid region to 0.4 to 0.5 mV in the damaged region.



(a) Pile 5, quadrant 2.



(b) Pile 5, quadrant 3.

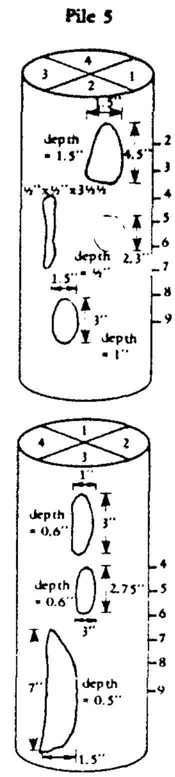
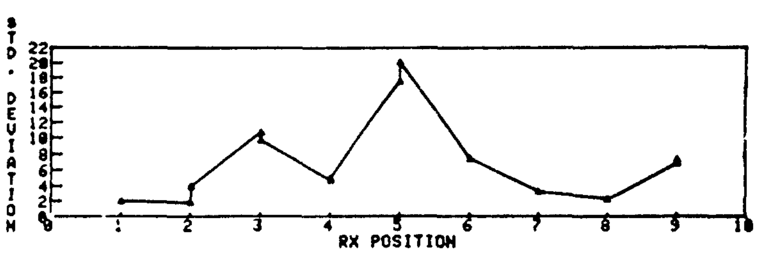
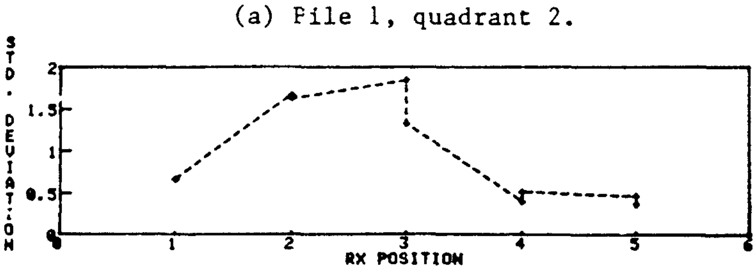


Figure 18. Ultrasonic field tests: standard deviation (100 μsec) versus position of receiver (RX) for Pile No. 5.



(a) Pile 1, quadrant 2.



(b) Support pile, quadrant 2.

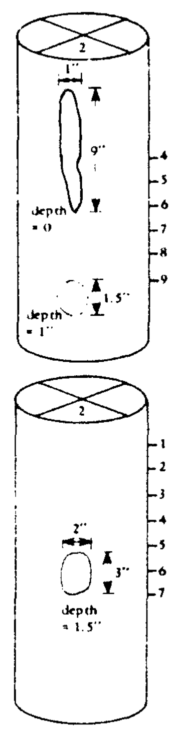


Figure 19. Ultrasonic field tests: standard deviation (100 μsec) versus position of receiver (RX).

Summary of Both Laboratory and Field Test Results. The final analysis of the ultrasonic inspection technique after the laboratory and field tests is based on the following criteria: (1) accuracy, (2) range of damage detection, (3) repeatability of readings taken, and (4) operational simplicity.

Accuracy is defined as the extent to which a given measurement agrees with the standard value for that measurement. One method for estimating accuracy uses the regression curves plotted in Figure 16. The R-value is shown for each curve. The test piles, standard, and 8335D show R-values of at least 0.6, indicating some relationship between the standard deviation and percent cross-sectional area loss. Complete dependence, however, requires that R = 1. Piles 4x1 and 5x have R-values equal to 0.02 and 0.06, respectively. Since R is close to 0, little relationship exists between the standard deviation and cross-sectional area loss for these piles. According to these results, the only correlation is for the standard pile which has only simulated damage with a maximum cross-sectional area loss of 26% and for pile 8335D which has extensive damage with a minimum cross-sectional area loss of 45%. Consistent correlation between standard deviation and percent cross-sectional area loss has not been found.

The range of damage detection can be evaluated by examining the regression curves (Figure 16). The curve for the standard pile (Figure 16a) shows that for a standard deviation value of 0.25 mV, the percent of cross-sectional loss could be between 0.0 and 20%. The regression curve for pile 8335D (Figure 16b) shows that a standard deviation value between 0.1 and 0.2 mV could indicate a cross-sectional loss in the range of 55 to 85%. Piles 5x and 4x1 show no decrease in standard deviation values with an increase in cross-sectional area loss. The variability of readings makes it impossible to discriminate the range of cross-sectional loss that can be detected.

The repeated ultrasonic readings varied in the same location. The variance between standard deviation readings was less that 0.05 mV. However, according to the regression curves, a small difference in standard deviation values (0.05 to 0.1 mV) can seriously affect the value of cross-sectional area loss.

The deployment of the ultrasonic equipment in an operational environment and subjected to actual use as in field testing showed the simplicity of using the ultrasonic device. The only function required of the diver inspecting the pile is to hold the transducer in the proper location. Both the distance between the transducers and the angle of orientation of the transducers in the transducer holder is pre-determined and pre-set.

IMPACT TESTING

Theory

Impact testing at NCEL was based on the simple hammer-sounding inspection method currently used by Navy divers to detect internal damage of timber piles. When a timber pile is struck with a hammer, a sharp ringing sound indicates a solid pile; a hollow or dull thud indicates a

damaged pile. Listening to the quality or tone of the acoustic response is a subjective process. NCEL conducted an engineering analysis of this acoustic inspection technique to quantify the hammer sounding method.

It is known that if the equilibrium condition of an object is disturbed by an impact, it is the nature of the object to transfer the force and the motion: to deflect, vibrate, resonate, and conduct sound (Ref 13). Upon impact, a timber pile will vibrate laterally, axially and radially. The overall resonant frequency response evaluated by SWRI showed no appreciable change with damage for the frequency response of lateral vibrations (Ref 8). The goal of the NCEL impact tests was to analyze the localized sound waves transmitted axially through the pile.

The hammer impact excites resonant modes of vibration affecting the quality of tone heard. Loudness, pitch, and timbre are the three fundamental quantities which characterize a tone. To the human ear, pitch is one attribute of auditory sensation for which sounds may be ranked and compared. Pitch is primarily a function of frequency, although intensity and waveform are also influential. A curve giving the relationship between subjective pitch and frequency at a fixed loudness is shown in Reference 14: pitch increasing with higher frequencies.

An objective approach to inspection of timber piles was devised that utilized a hydrophone or an accelerometer to record the acoustic response of the pile to the hammer impact. An instrumented hammer excited the timber pile with a nearly constant force over a broad frequency range. The time domain signal was used to generate the Fast Fourier Transform (FFT) of the signal for later analysis.

When disturbed by an impulse forcing function (hammer tap), the pile resonates at its damped natural frequency. It was anticipated that an analysis of the frequency spectrum would show a higher frequency response (higher pitch) for solid timber piles and lower frequency response for damaged piles. Correlation between the axial frequency response of the timber pile and the amount of cross-sectional wood loss was desired. Consequently, the following variations in the signals from solid and damaged wood were investigated: (1) changes in bandwidth, (2) number of discrete frequency bands (peaks), and (3) amplitude and frequency of the highest energy peaks. Laboratory and field tests were conducted.

Types of Impact Testing

NCEL impact testing concentrated on two basic applications. Both approaches deal with impulse impact and the analysis of the frequency response of the timber pile. The primary difference is the specific equipment used to measure the acoustic timber response after impact; either a hydrophone or an accelerometer was used to record the acoustic response.

Ideally, both the stimulus (impulse force) and the frequency response (axial vibration of the pile) could be objectively measured. The overall testing procedure for the impact tests was divided into two separate series: (1) hydrophone impact tests with an instrumented hammer and a hydrophone and (2) accelerometer impact tests with an instrumented hammer and an accelerometer. A detailed description for each series follows.

Equipment

Hydrophone Description.

The hydrophone impact test equipment consisted of:

- a Bruel and Kjaer (B&K) hydrophone and safety case
- a voltage supply source for the hydrophone (B&K)
- a Piezotronic (PCB) instrumented hammer
- a programmable digital oscilloscope (Tektronix model 7854)
- a computer (Tektronix model 4052), printer, and tape drive

The hydrophone and voltage supply source are shown in Figure 20. This equipment was selected based on availability, economic constraints and desired characteristics.

The B&K hydrophone had the desired characteristics and was readily available at NCEL. The hydrophone parameters are:

- Piezoelectric transducers
- Frequency range of 1 Hz to 125 Hz
- Flat frequency response up to 70-80 kHz
- Omnidirectional
- Sensitivity of -184 db Ref 1V/μPa
- Built-in, solid state preamplifier

Instrumented hammer kits are commercially available for behavior testing of a wide variety of structures. PCB Piezoelectronics Incorporated manufactures and supplies hammer kits as complete calibrated systems. A technical representative from PCB Piezotronics recommended the General Purpose impulse hammer. This impulse hammer was selected because structures (like timber pilings) could be tested at low, medium, and high frequencies. The impulse hammer contains a built-in accelerometer (Figure 21) designed to measure the impact generated by the specific hammer. The impulse hammer parameters are:

- Forced transducer range of 0-500 lbf
- Sensitivity of 10 mV/lbf
- Resonant frequency of 70 kHz
- Hammer mass of 0.3 lb
- Tip diameter of 0.5 inch

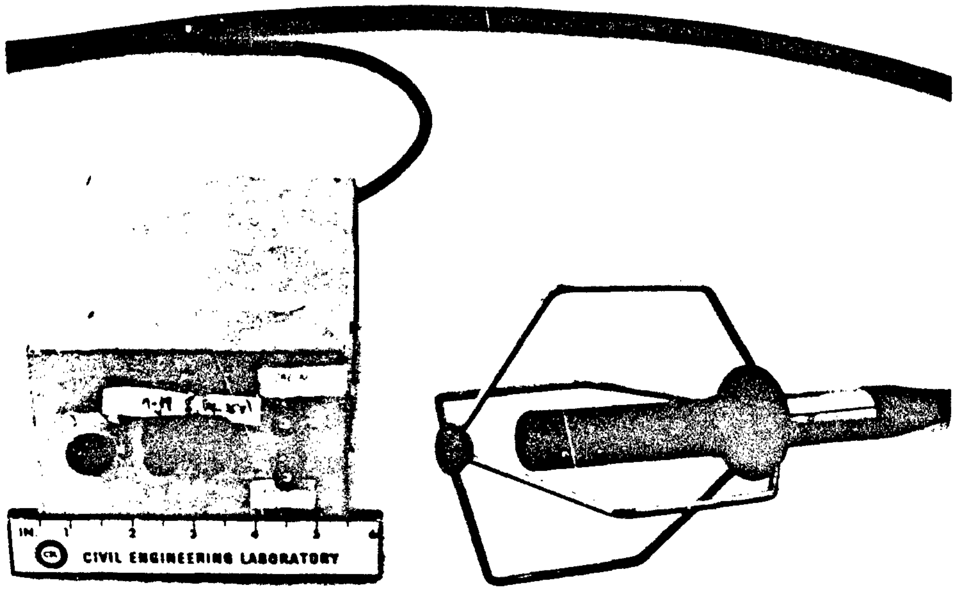


Figure 20. Hydrophone and voltage supply source.

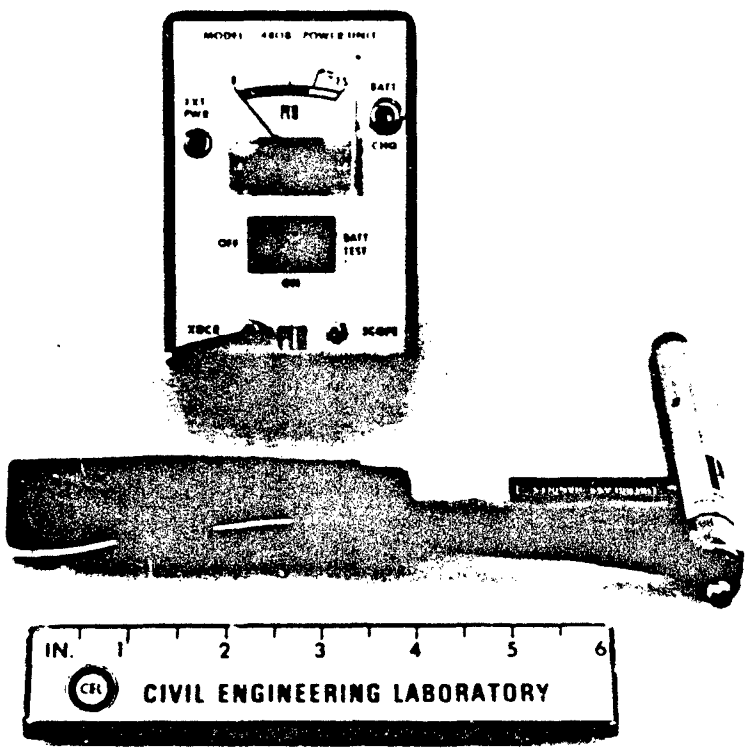


Figure 21. Impulse hammer with built-in accelerometer.

Accelerometer Description. The equipment used for the accelerometer impact tests was exactly the same as described for the hydrophone impact tests except an accelerometer was used in place of the hydrophone (Figure 22). A quartz accelerometer was supplied with the instrumented PCB hammer. This accelerometer offers exceptionally good low frequency response. The accelerometer parameters are:

- Range ±500g
- Resolution of 0.02g
- Sensitivity of 10 mV/g
- Resonant frequency 45 kHz
- Frequency range of 1 to 5000 Hz

Laboratory Procedure

Laboratory impact testing was conducted on the same test piles described earlier in the NCEL laboratory ultrasonic tests. The initial preparations made were also the same as those made before ultrasonic testing began.

In the general procedure for the impact tests, the timber pile was hit in the desired, previously marked location, and the acoustic response of the timber pile was picked up with the hydrophone or accelerometer at a set distance away from the impact position. Both the hydrophone and accelerometer were hand-held. The hydrophone was held approximately 2 inches away from the timber pile. The accelerometer was held in intimate contact with the timber pile to pick up the impact-generated signal.

One technician and one engineer performed the impact tests. The technician struck the timber pile with the PCB hammer, held the hydrophone approximately 2 inches from the pile or held the accelerometer directly against the pile in the desired location, and kept the test pile from moving during the test. The test pile lay horizontally in the saltwater test tank.

Both the impact signal of the hammer and the received outgoing signal were sent directly to the programmable oscilloscope through connecting cables. The digitized waveforms for both the impact and received signals were displayed on the oscilloscope CRT view screen. A schematic of the impact test equipment configuration is shown in Figure 23. Digitized waveforms of both the input and output signals were stored on a magnetic tape for later analysis.

The distance between the impact position and the placement of the hydrophone or accelerometer depended on the test pile being evaluated. The procedure was to hit the test pile at every marked line and to pick up the received signal at the succeeding line. The length of the standard pile was marked with 20 lines spaced 3 inches apart; the other test piles (5x, 4x1, 8335D, 8323E) were marked lengthwise into 6-inch increments. Thus, the localized axial response between the marked lines was received. Each impact signal and received signal was repeated to verify the reproducibility of the test results.

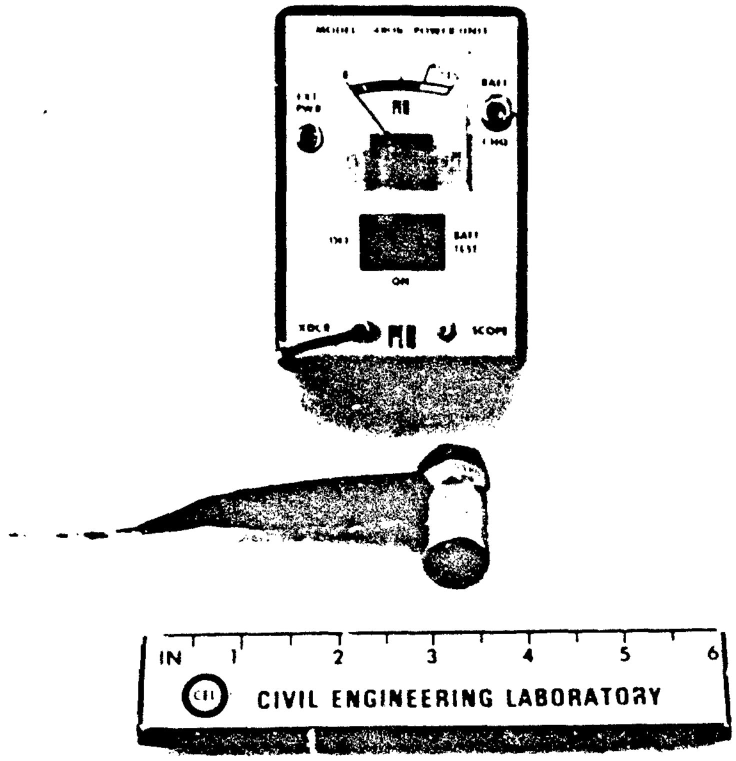


Figure 22. Quartz accelerometer.

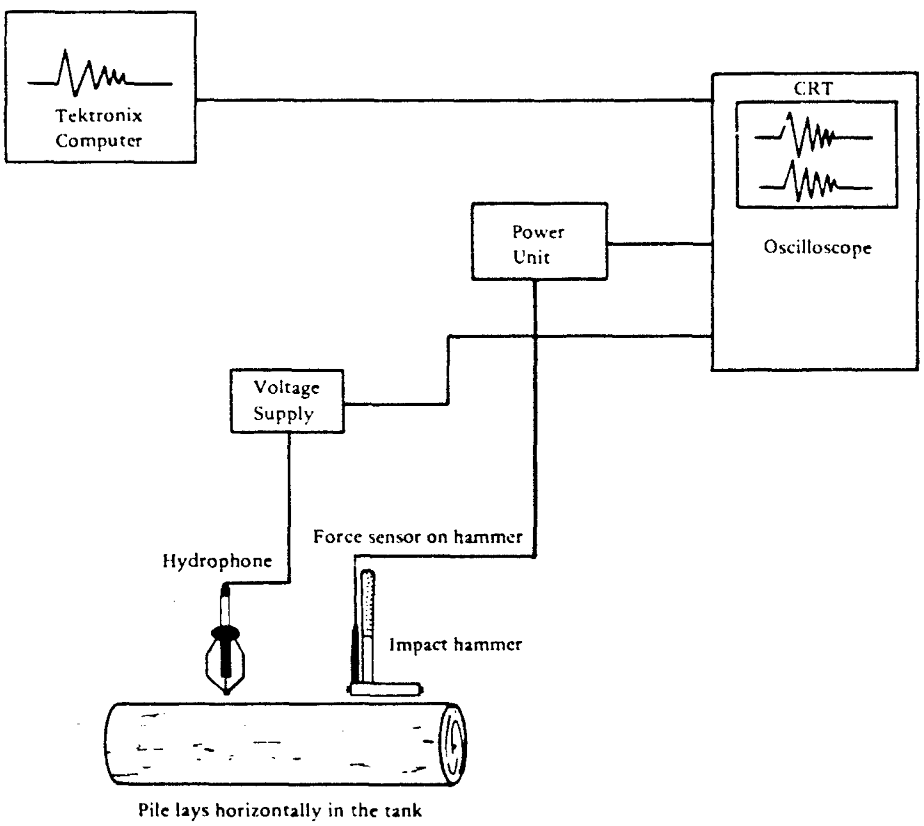


Figure 23. Schematic of impact test configuration.

The data recorded for each series of impact tests (whether hydrophone or accelerometer) were as follows:

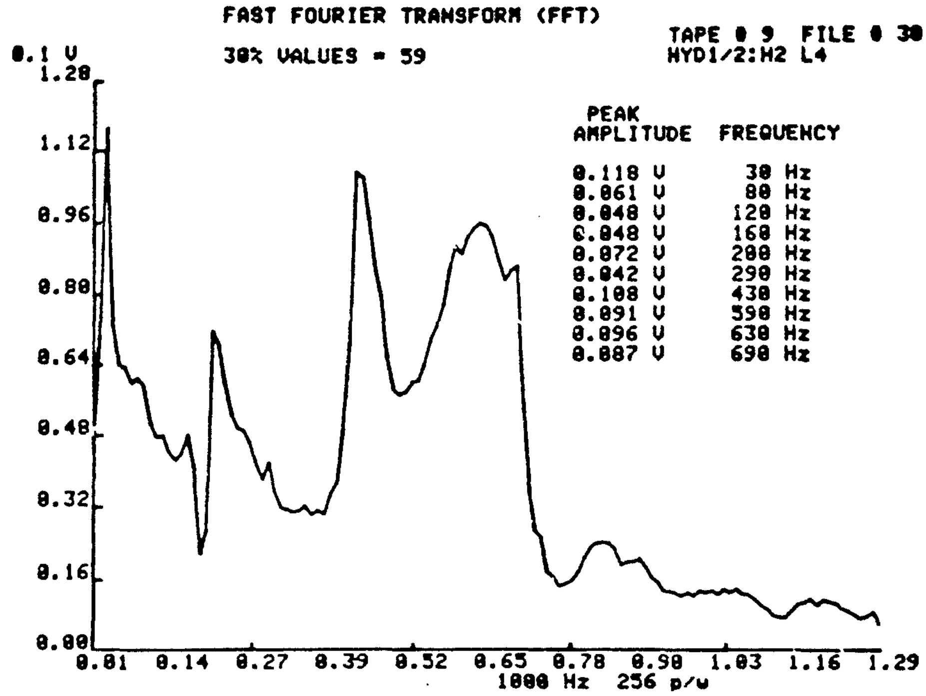
- The digitized impact waveform
- The digitized response waveform received by the hydrophone or the accelerometer
- The location of the hammer impact and of the hydrophone or accelerometer
- The separation distance between the impact and the received response
- Description of the pile, including a sketch showing the damage in test locations
- Settings on the programmable oscilloscope
- Time, date, and location of the test
- Tape and file number that locates the stored waveform
- Any changes in test setup or execution
- Comments, including noticeable changes in recorded waveforms

Laboratory Test Results

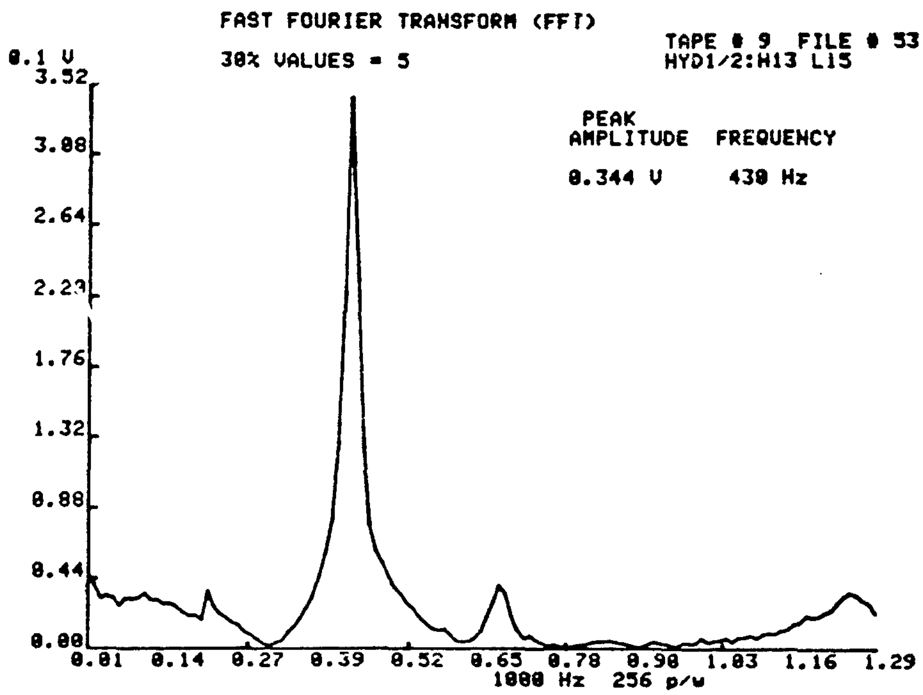
The first series of hydrophone impact tests were carried out on the standard pile with its simulated borer damage. These tests revealed that the damaged portion of the pile had more discrete frequency bands with smaller amplitudes than the solid portion, which had fewer narrow frequency bands with higher amplitudes (Figure 24). Repeated tests in the same location resulted in similar waveforms and corresponding FFT's, demonstrating the repeatability of the hydrophone impact tests.

The accelerometer impact tests verified the hydrophone impact test results; however, some discrepancies between repeated tests began to develop. The accelerometer has a higher sensitivity and can detect ambient noise to a greater extent than the hydrophone. Readings were not always reproducible.

The PCB hammer has an obvious effect on the impulse transmitted through the timber pile and generates a transient (impact) excitation signal. This is evidenced by a short narrow constant energy spike. A single impulse is vital to initiating a wide range of frequencies at essentially constant energy into the timber pile. To be sure that the impulse generated by the PCB hammer was a single constant energy pulse, the FFT of the input signal was analyzed.



(a) Damaged region.



(b) Solid region.

Figure 24. Frequency spectrum: damaged versus solid region of standard test pile.

In a series of tests, the effect of the hammer orientation on the force input to the timber pile was assessed. The PCB hammer held at three different orientations was used to strike a solid pile: handle of the hammer parallel to the axis of the pile when vertical; handle of the hammer perpendicular to the axis of the pile when vertical; and handle of the hammer perpendicular to the axis of the pile when horizontal.

The hammer orientation affected the amplitude and frequency band of the input force and output signal received (Figure 25). A standard method of hitting with the handle of the hammer perpendicular to the axis of the laboratory test pile laying horizontally in the water was established.

The hydrophone and accelerometer impact tests were repeated on the standard pile and conducted on the same test timber piles used previously. The data collected during the impact laboratory tests are shown in Figures 26 and 27. These curves generally exhibit a decrease in frequency of the highest amplitude peak with an increase in percent cross-sectional wood loss.

Figure 26 shows the regression analysis of the hydrophone data collected for all of the laboratory test piles. In addition, the R-value for the curve, the standard deviation, and the standard error of estimate are shown. The standard deviation is very high, resulting in a high standard of error. Figure 27 shows the regression analysis of the accelerometer data collected for the standard, 5x, and 4x1 test piles; again, the standard error is very high.

The other variations expected between solid and damaged wood, which included changes in bandwidth and number of discrete frequency bands, were evaluated. However, no correlation to the percent of cross-sectional wood loss could be found.

As expected, the solid areas of the test piles generally had a higher frequency response than the damaged regions, but this was not true for every test. Variations were observed between repeated tests, and several contradictions between damaged and solid regions were found.

Impact Field Testing

Field impact tests were conducted at the corrosion test pier on the piles inspected with the ultrasonic test equipment. Preparations made before impact testing were the same as those outlined in the NCEL Ultrasonic Field Testing section. The only difference was that the hydrophone or the accelerometer rather than the transducers (receiver and transmitter) was employed.

The general procedure followed for the impact field tests closely resembled the procedure followed for the laboratory impact tests described in the preceding section. However, the high electrical noise level in the cable lines and ambient noise level in the harbor severely distorted the impact signal of the PCB hammer. Consequently, a 3-pound sledge hammer was utilized during the field impact tests, and the impact imparted to the timber pile was not recorded.

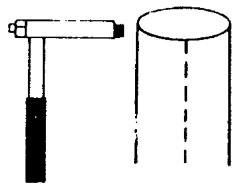
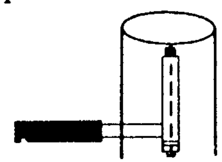
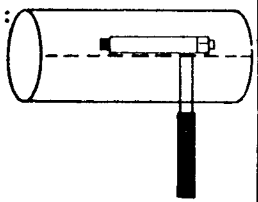
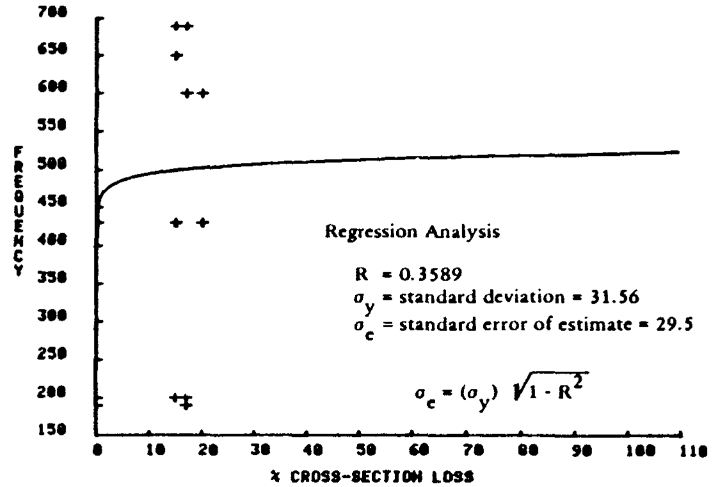
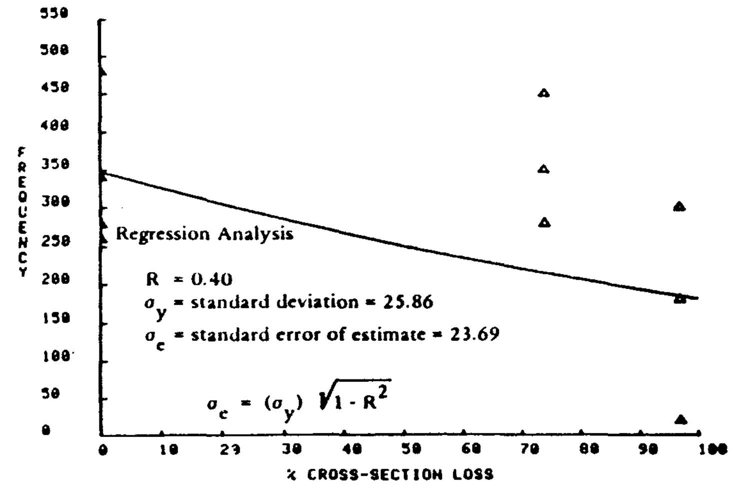
Description	Fast Fourier Transform			
	Hammer Frequency Range (Hz)	Amplitude (V)	Accelerometer Frequency Range (Hz)	Amplitude (V)
Pile is vertical and the handle of the hammer is parallel to the axis of the pile. Example: 	A. 20 - 1,080 B. 20 - 240 C. 20 - 960 D. 20 - 300	3.59 .58 .36 .45	40 - 940 40 - 920 60 - 920 60 - 880	.41 .36 .45 .47
Pile is vertical and the handle of the hammer is perpendicular to the axis of the pile. Example: 	A. 20 - 220 B. 20 - 200 C. 20 - 100 D. 20 - 200	.46 .71 .71 .72	40 - 760 40 - 900 80 - 1,060 40 - 860	.62 .32 .54 .43
Pile is horizontal and the handle of the hammer is perpendicular to the axis. Example: 	A. 20 - 200 B. 20 - 220 C. 20 - 580 D. 20 - 440	.71 .43 .43 .35	20 - 760 20 - 840 20 - 920 760 - 800	.18 .19 .12 .49

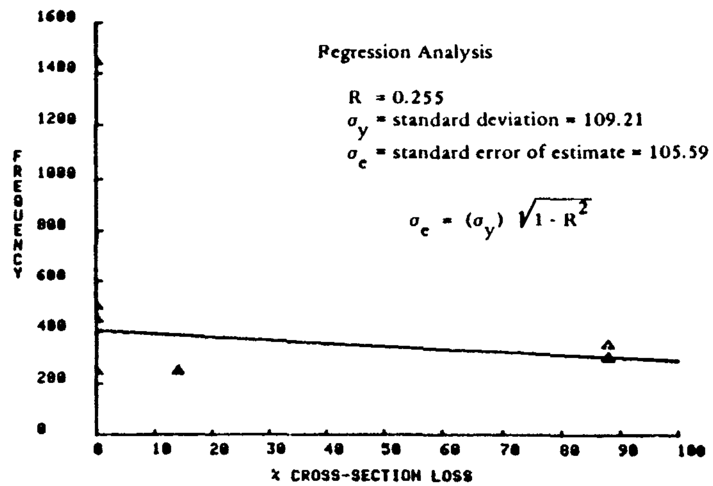
Figure 25. Effect of hammer orientation during accelerometer impact tests.



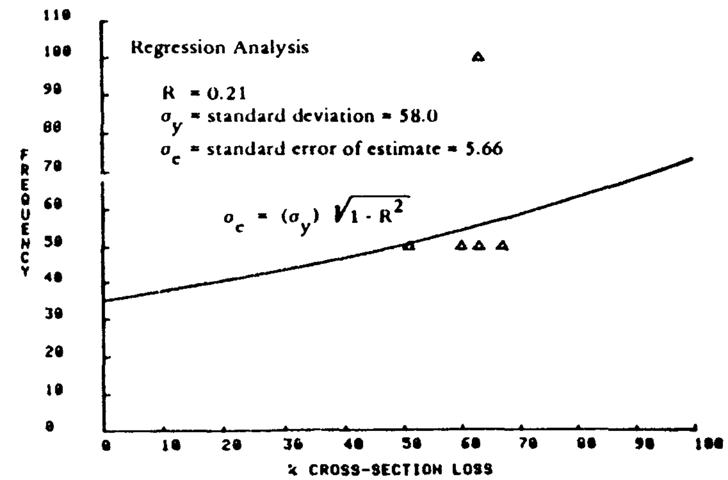
(a) Standard pile,



(b) 5X pile.

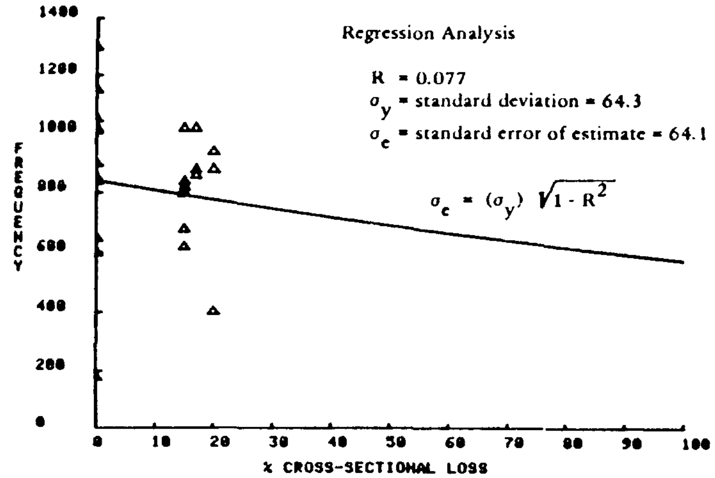


(c) 4X1 pile.

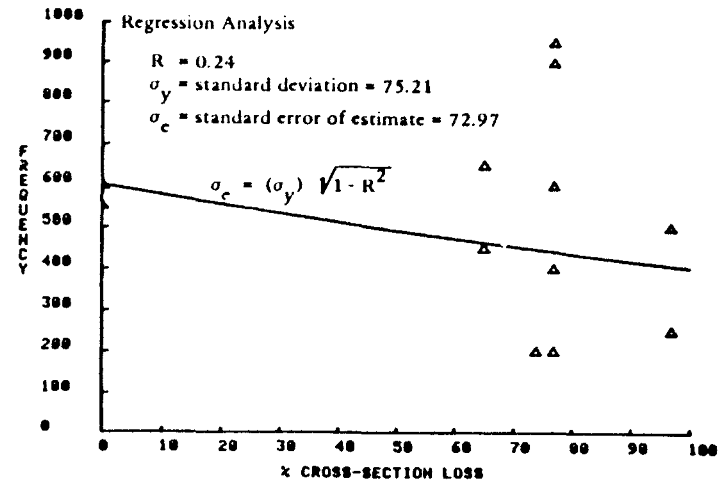


(d) 8335D pile.

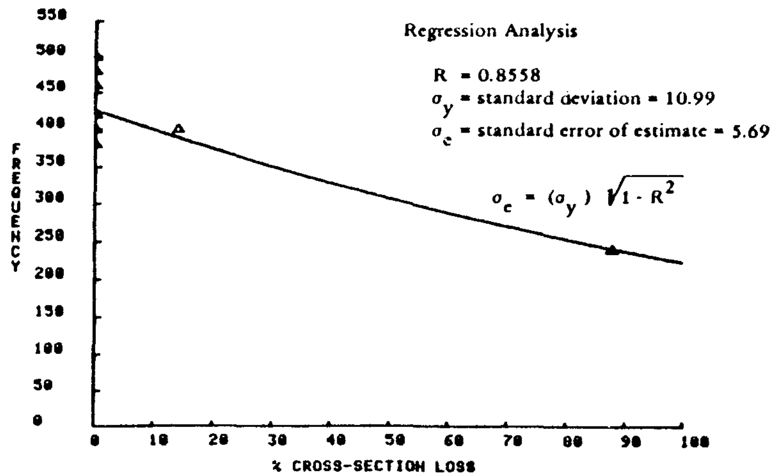
Figure 26. Regression analysis curves for laboratcry piles tested during hydrophone-impact tests.



(a) Standard pile.



(b) 5X pile.



(c) 4 pile.

Figure 27. Regression analysis curves for laboratory piles tested during accelerometer-impact tests.

Hydrophone. Field testing is vital to determination of the accuracy, ease of deployment, and reliability characteristics of any new technique because of the need for testing in an uncontrolled, anticipated operational environment. The hydrophone tests conducted at the corrosion pier amplified the need for a standardized, uncomplicated inspection technique. Explicit direction had to be given, and followed, for uniformity during testing.

During several periods in the hydrophone tests, subjective human reasoning and variations in procedures affected the results. The hydrophone test procedures varied in the following ways: (1) the hammer impact was inconsistent due to the differences in each individual blow and (2) at first, the hydrophone was touching the pile, but later was held approximately 1-1/2 inches away from the pile. When these variations were recognized, a standard procedure was devised for the divers. The divers were explicitly instructed to hold the hydrophone 1-1/2 inches away from the timber pile being tested at the line marking below the impact region. In addition, a consistent hammer impact was needed. The same exact strength behind each hammer blow was impossible, but more consistent impact was achieved.

The data recorded for each series of impact tests performed on the four harbor test piles were the same as that outlined for the laboratory impact tests. Minor variations in the data collected included: (1) the digitized impact waveform was not recorded and (2) a description of each test pile and damage in test locations were recorded on video tape as well as in sketches.

Accelerometer. The procedure followed for the accelerometer impact tests was nearly the same as that outlined for the laboratory impact tests. The accelerometer tests were conducted on only two quadrants of each of the four harbor test piles.

Field Test Results

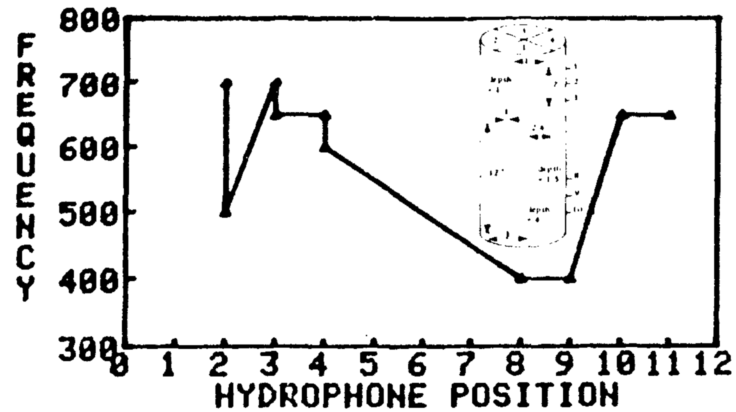
The impact test equipment, like the ultrasonic test equipment, could only be evaluated in the field for its ability to detect external damage. Figures 28 and 29 present test results showing the frequency shifts in damaged and undamaged regions of the harbor test piles for the hydrophone and accelerometer impact field tests, respectively.

Figure 28a shows the shift in frequency (in quadrant 1) of the highest amplitude peak in the frequency spectrum from a range of 500 to 700 Hertz in the solid regions to 400 Hertz in the damaged region of pile no. 8. The accelerometer data obtained for the same pile (Figure 29a) were inconsistent with the hydrophone data. No correlation could be established between the frequency (corresponding to the highest energy peak) and the amount of external damage.

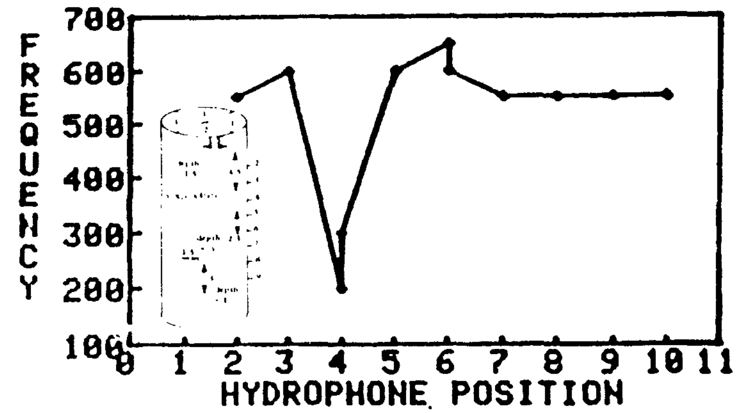
The greatest amount of damage on pile no. 5 was in quadrant 2 below line 3; the lowest frequency is observed in this region (Figure 28b). The damage in quadrant 3 of pile no. 5 was insignificant, and the accelerometer data collected here show no shift in frequency (Figure 29b).

The data collected on harbor pile no. 1 show an increase in frequency in traveling from a damaged region to a solid region (Figure 28c).

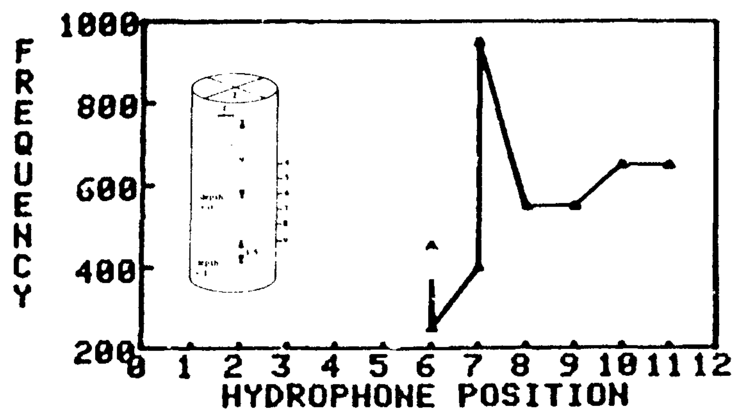
The Support pile results show that the frequency remains constant along the pile (Figure 28d).



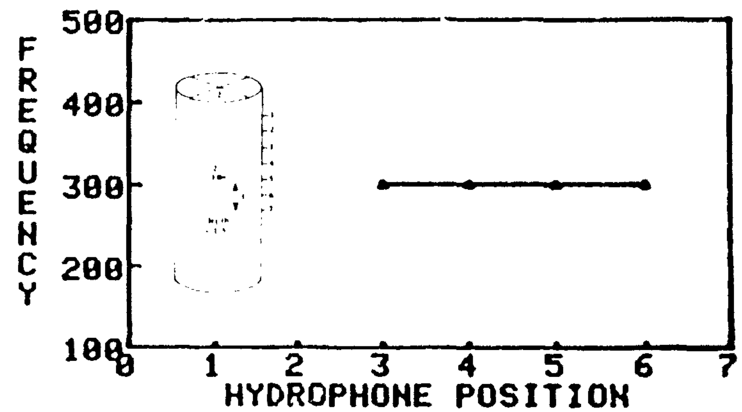
(a) Pile No. 8, Quadrant 1.



(b) Pile No. 5, Quadrant 2.

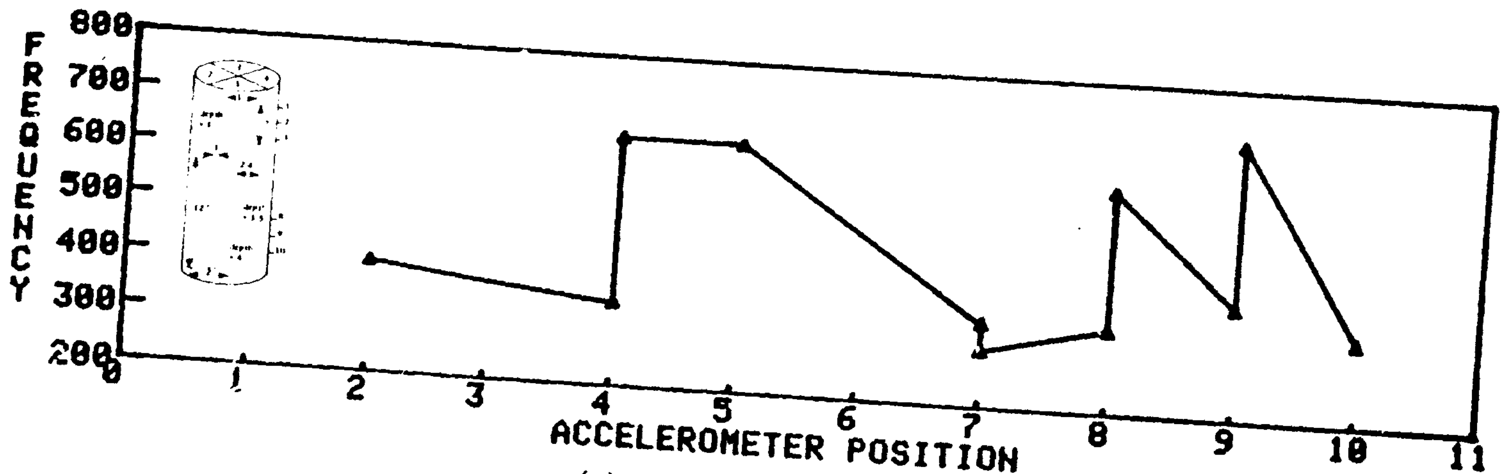


(c) Pile No. 1, Quadrant 2.

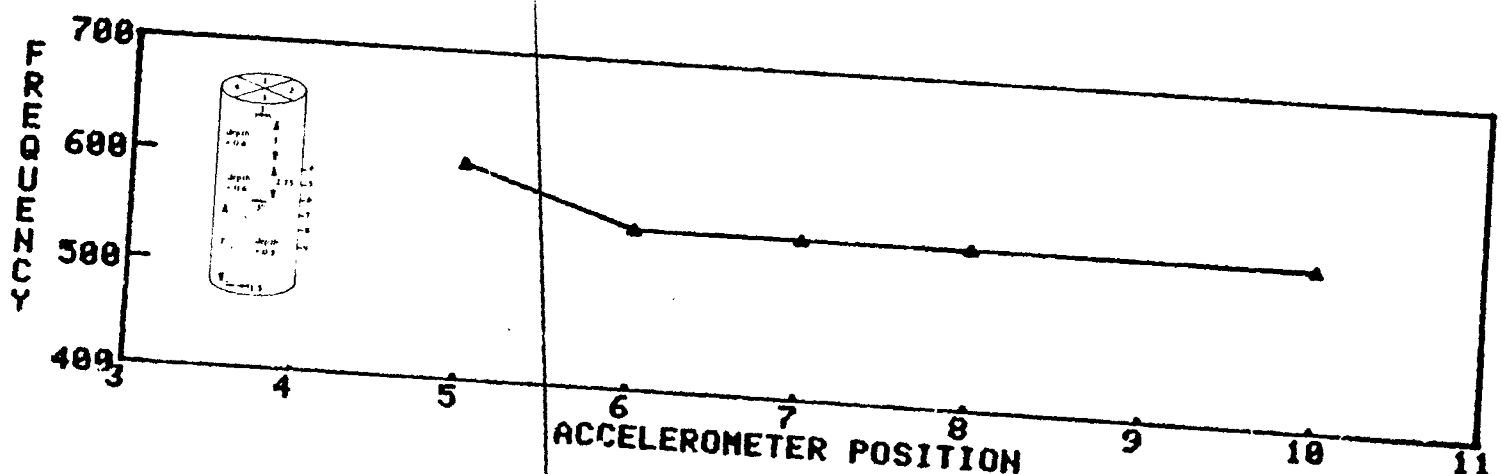


(d) Support pile, Quadrant 2.

Figure 28. Hydrophone field impact tests: frequency shift versus position of the hydrophone.



(a) Pile No. 8, Quadrant 1.



(b) Pile No. 5, Quadrant 3.

Figure 29. Accelerometer impact test: frequency shift versus accelerometer position.

Summary of Impact Test Results

Like the ultrasonic tests, the impact tests were evaluated on accuracy, range of damage detection, repeatability of readings taken, and operational simplicity.

The accuracy associated with the impact tests is ±50%. Frequency analysis of the impact response can be used only to detect internal damage between 50 and 100% of the total cross-sectional area. The range of detection of external damage, however, is not limited to severe damage; a decrease in amplitude and frequency was observed for external damage constituting only a 15% cross-sectional area loss.

The impact tests were not reproducible. The variance in frequency shifts between repeated tests was extremely high (300 to 700 Hertz).

From the standpoint of assessing the operational simplicity of the impact inspection technique, the true test was actual use in Port Hueneme harbor. Although the impact procedure was relatively simple to perform, diver technique greatly influenced the signal generated and received. This adversely affected the reliability and consistency of the results.

CONCLUSIONS AND RECOMMENDATIONS

Three timber inspection techniques - computerized axial tomography, ultrasonic, and impact - have been presented. The following conclusions and recommendations are made:

1. At this time, only the conceptual design of an underwater computerized axial tomography inspection system can meet the accuracy requirements (Ref 1) for detection of internal defects in wood. Because of the developmental nature of underwater tomography and cost, further work on development of an underwater CAT system has been postponed.

2. A decrease in standard deviation of the received ultrasonic signal with an increase in percent cross-sectional area loss has been observed for a few of the laboratory and harbor test piles, but a consistent correlation has not been found. A shift in standard deviation reading from the average reading taken on a solid section for each pile could be an indication of internal or external damage, a knot, or a change in grain orientation. Therefore, a shift in ultrasonic reading indicates a potentially damaged region but must be confirmed with a visual inspection or other NDT technique.

3. The ultrasonic test results indicate the low frequency ultrasonic system cannot meet the accuracy requirements in Reference 1. However, it would be advantageous to develop an ultrasonic system similar to the NCEL system to increase the confidence and reliability of inspection data compared to a visual inspection. In addition, the probability of detecting internal damage is greater during an ultrasonic inspection than during a visual inspection.

4. Frequency analysis of the acoustic response after impact can only be used to detect excessive internal damage (50% or more). Many factors involved in the impact testing procedure affect the signal received:

orientation of the hammer, strength of the hammer blow, placement of the hydrophone or accelerometer along the pile length, and any movement of the hydrophone or accelerometer during testing. Deciphering and eliminating the individual causes for discrepancies in the received signals is extremely difficult and highly unlikely. Therefore, it is recommended that further pursuit of the impact testing technique be discontinued.

5. An economic cost/benefit analysis of each of the technically feasible timber inspection techniques is planned in this fiscal year. Subsequently, one of the timber inspection systems should be selected for prototype development based upon measurement accuracy and economic cost/benefit.

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